ELECTRIC POWER RESEARCH INSTITUTE

Embedded Solution Approaches Through Equipment Design Strategies

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Embedded Solution Strategies

- Use “Selective Power Conditioners” on susceptible loads

CVT

DPI

DySC

CoilLock

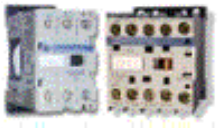
Low Voltage Ride Through Module

- Embed the Solution through proper design, configuration and component selection strategies

Vacuum Pumps

Contactors

DC Power Supplies


Relays

- Utilize a *Combination* of both strategies

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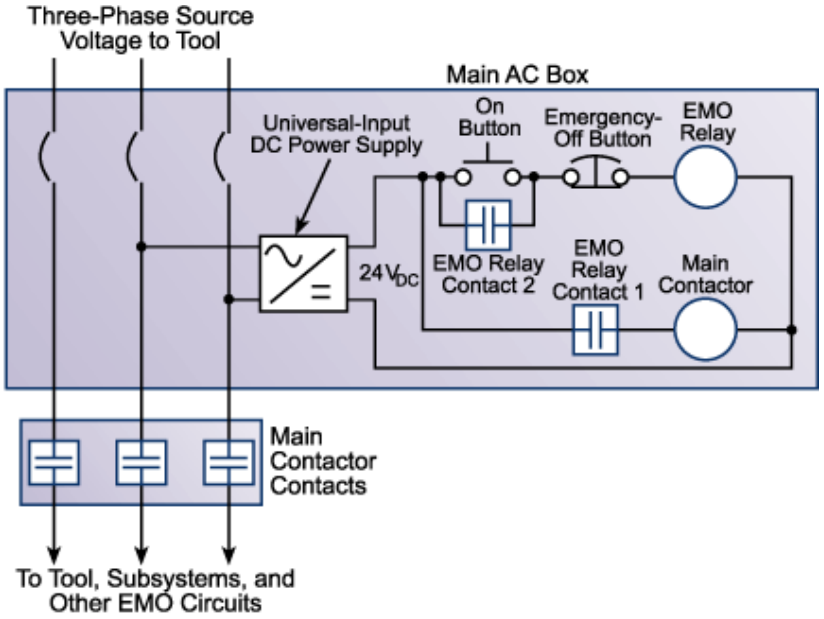
Method 1: Design with DC Power

- One of the best methods of increasing the tolerance of control circuits is to use direct current (DC) instead of alternating current (AC) to power control circuits, controllers, input/output devices (I/O), and sensors.
- DC power supplies have a “built-in” tolerance to voltage sags due to their ripple-correction capacitors, whereas control power transformers (CPTs) and AC components do not have inherent energy storage to help them ride through voltage sags
- Many OEMs are moving in this direction to harden their equipment designs



DC Powered Emergency Off Circuit

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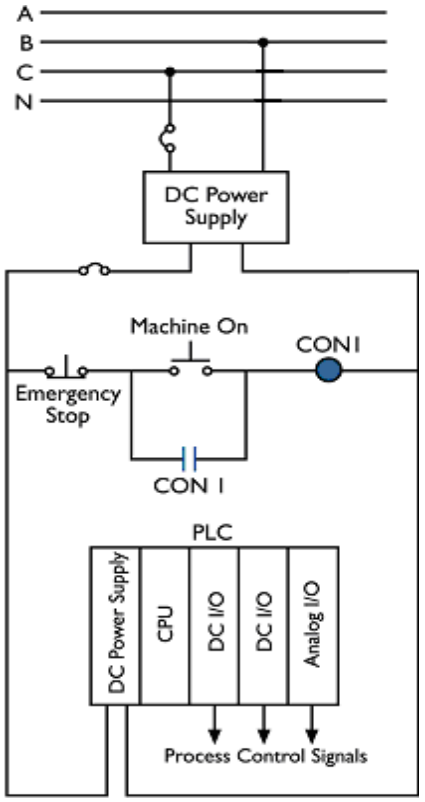
Demonstration Time – PLC using DC Power Supply Rather Than CPT

- How Much Better is the DC solution?
  - Depth of Sag
  - Duration of Sag
- What other benefits does DC have?
- What are some design considerations with DC?



DC Powered PLC Circuit

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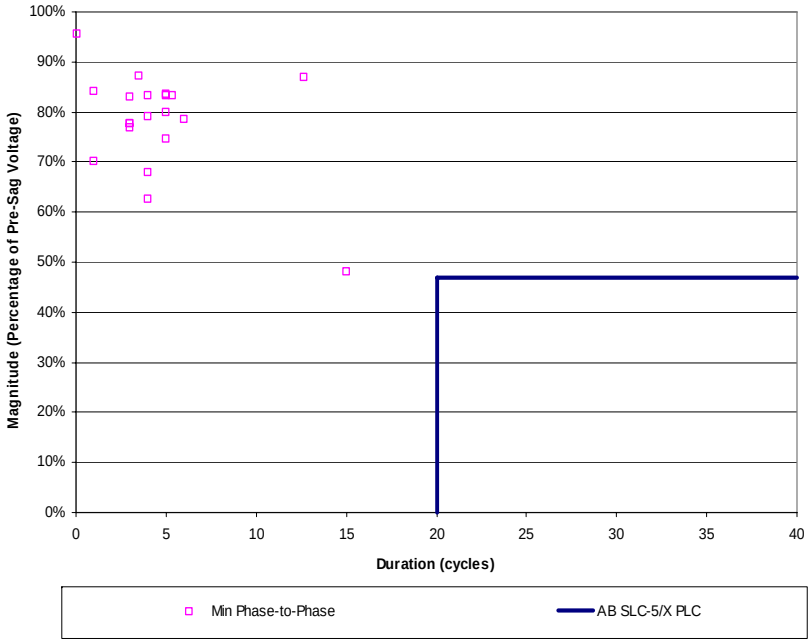
DC Powered PLC System in Weld Shop

(3) Three phase input Siemens SITOP DC Power Supplies

AB SLC-5/x PLC with DC I/O



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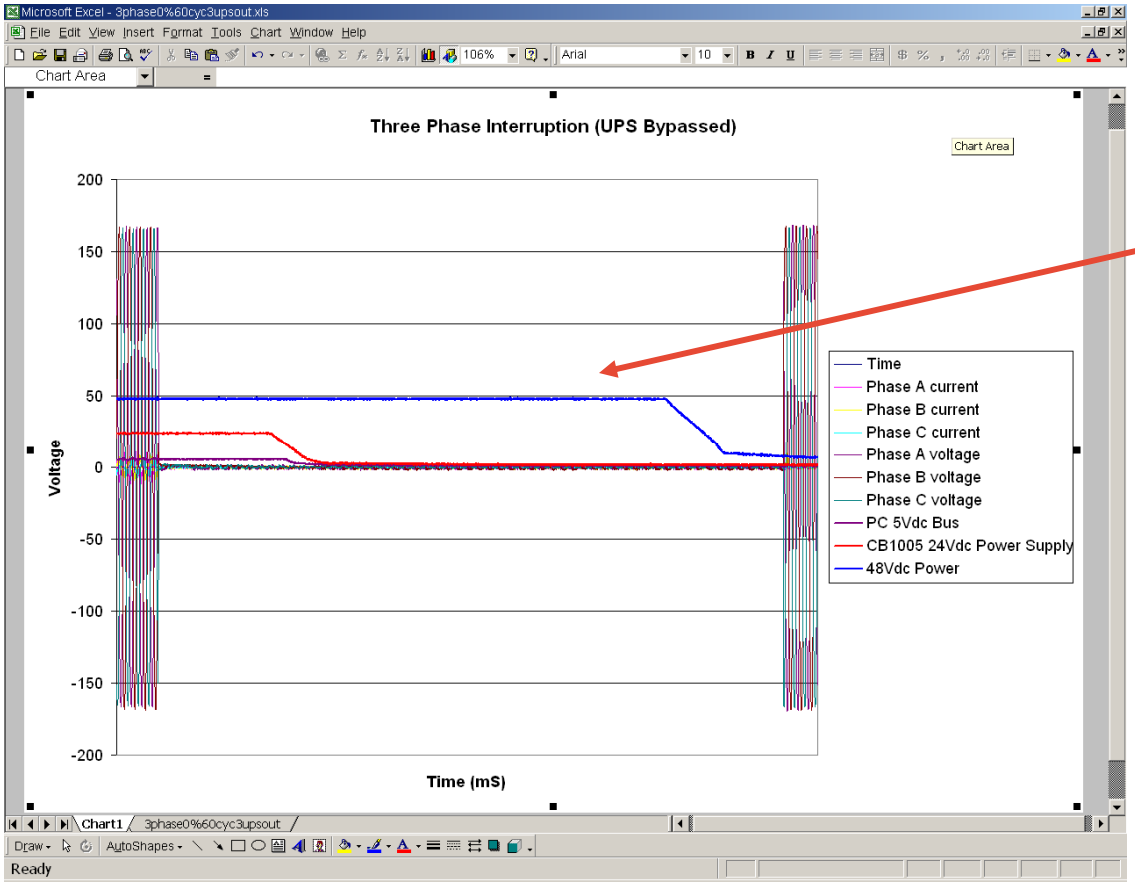
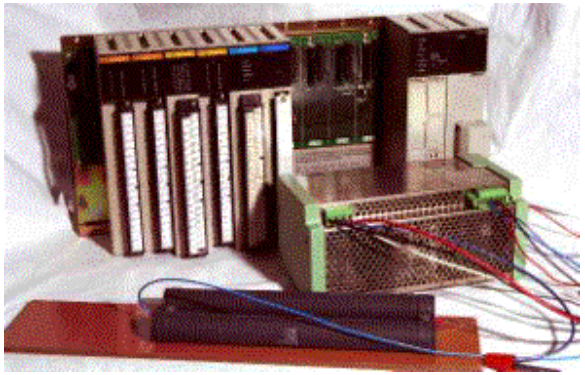
For 480Vac 3-Phase Systems One Can Utilize a 3-Phase 480Vac Input DC Output P/S



FXC7000
Front and Rear Views

Power One



Phoenix Contact

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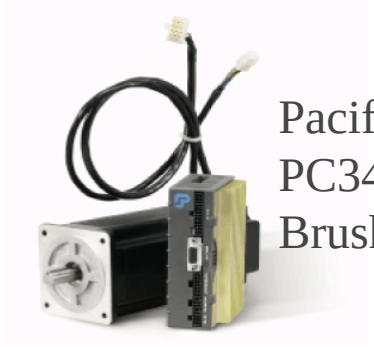
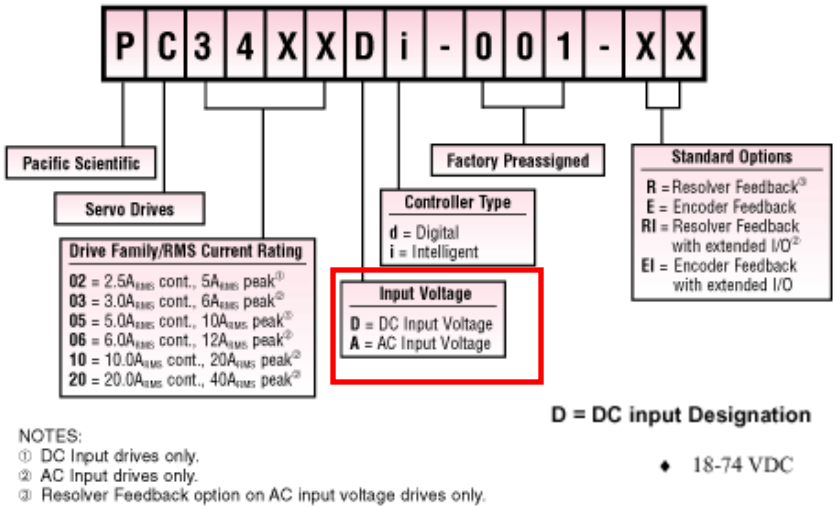
Servo Drives Can Be Specified for DC Input Rather Than AC Input

- Many items such as Servo Drives can be bought with AC input or DC input options
- Specifying a DC input option and utilizing a robust DC power supply scheme can make servo controls robust to voltage sags
- Removes Voltage Sag Issue from Servo Drive



Pacific Scientific
PC3400 Series Digital
Brushless Servo Drives


P C 3 4 X X D i - 0 0 1 - X X
Pacific Scientific
Servo Drives
Drive Family/RMS Current Rating
02 = 2.5A cont., 5A peak①
03 = 3.0A cont., 6A peak②
05 = 5.0A cont., 10A peak②
06 = 6.0A cont., 12A peak②
10 = 10.0A cont., 20A peak②
20 = 20.0A cont., 40A peak②
Controller Type
d = Digital
i = Intelligent
Input Voltage
D = DC Input Voltage
A = AC Input Voltage
Factory Preassigned
Standard Options
R = Resolver Feedback③
E = Encoder Feedback
RI = Resolver Feedback with extended I/O②
EI = Encoder Feedback with extended I/O
D = DC input Designation
♦ 18-74 VDC
NOTES:
① DC Input drives only.
② AC Input drives only.
③ Resolver Feedback option on AC input voltage drives only.

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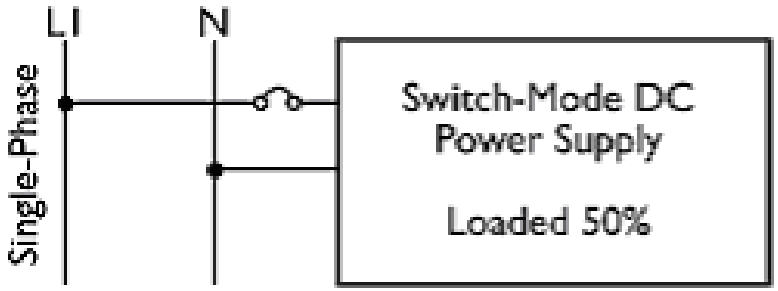
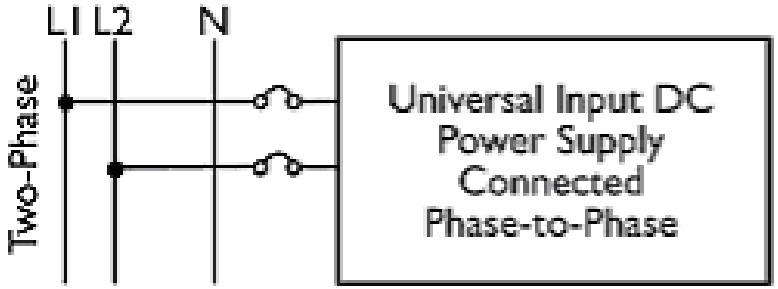
Summary of Robust Power Supply Strategies



Switch-Mode DC Power Supply

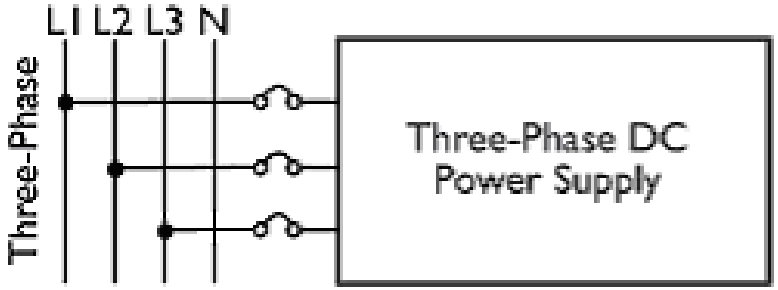
Loaded 50%

Most relevant to single-phase circuits. In order to ensure robustness, design for 50% loading.



Universal Input DC Power Supply Connected Phase-to-Phase

Most relevant to 208-VAC, three-phase systems. Input voltage ranges from 85 VAC to 264 VAC connected phase-to-phase. Will maintain output down to 41% nominal input voltage even at 100% load.



Three-Phase DC Power Supply

Most relevant to 480-VAC, three-phase systems. Power supply is impervious to single-phase voltage sags and momentary interruptions.

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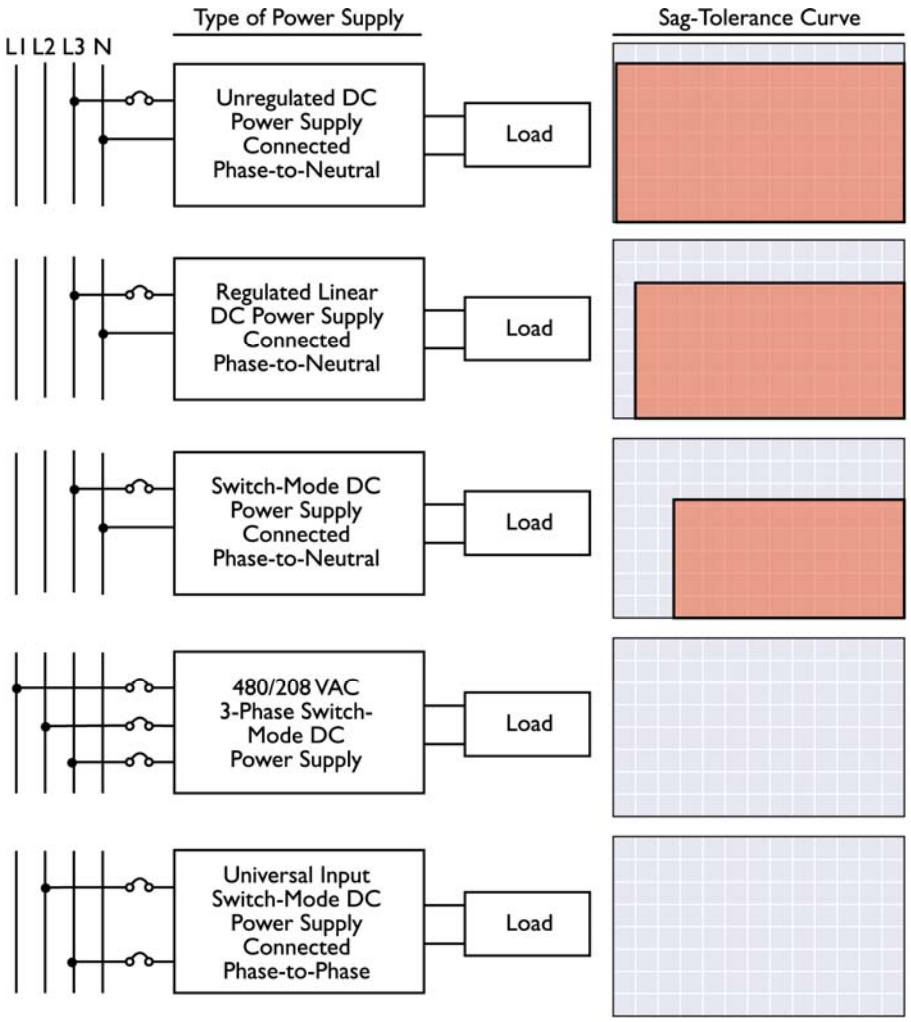
Summary of Robust Power Supply Strategies: Relative Power Supply Response at 100% Loading



Ride-Through for Single-Phase Voltage Sags

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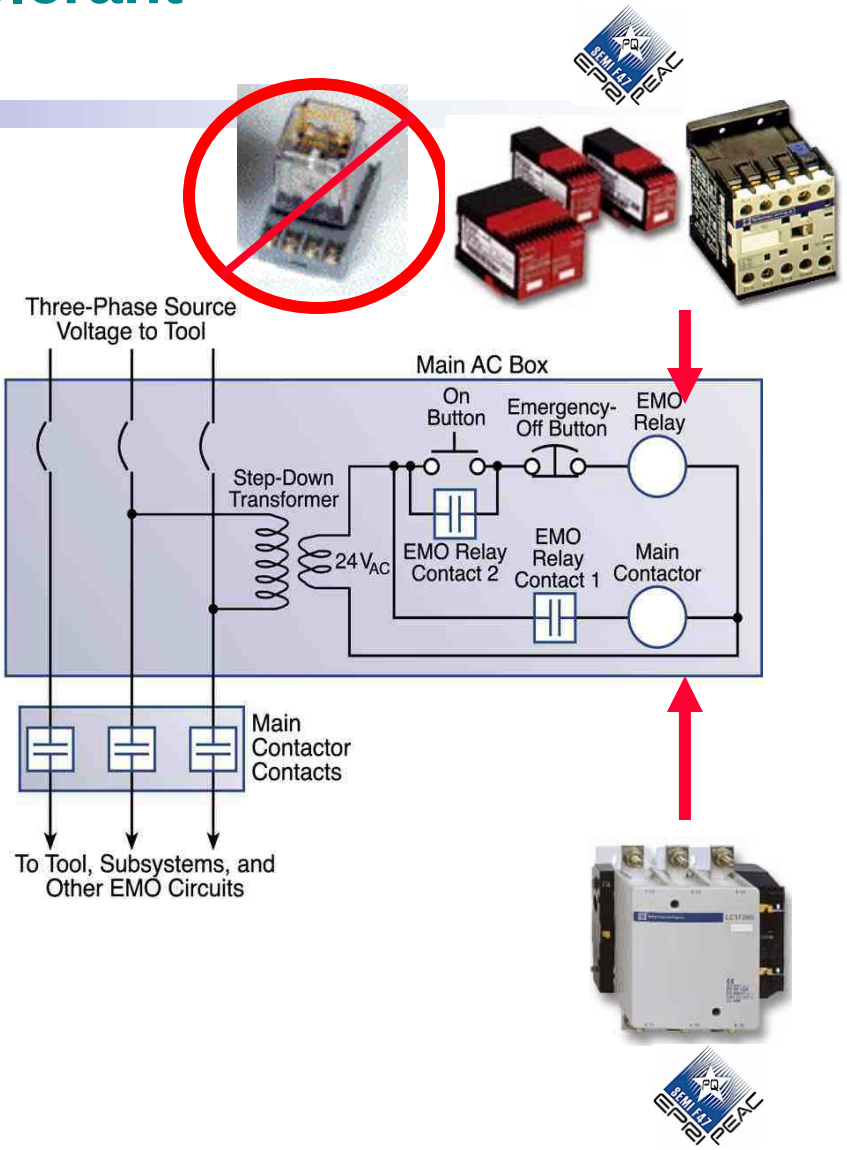
Method No. 2: Utilize Sag Tolerant Components

- IF AC Relays and Contactors are used in the semiconductor tool design, then utilize compliant devices.
- Consider response at both 50 and 60 Hz.
- We have certified a many relays and contactors to SEMI F47.



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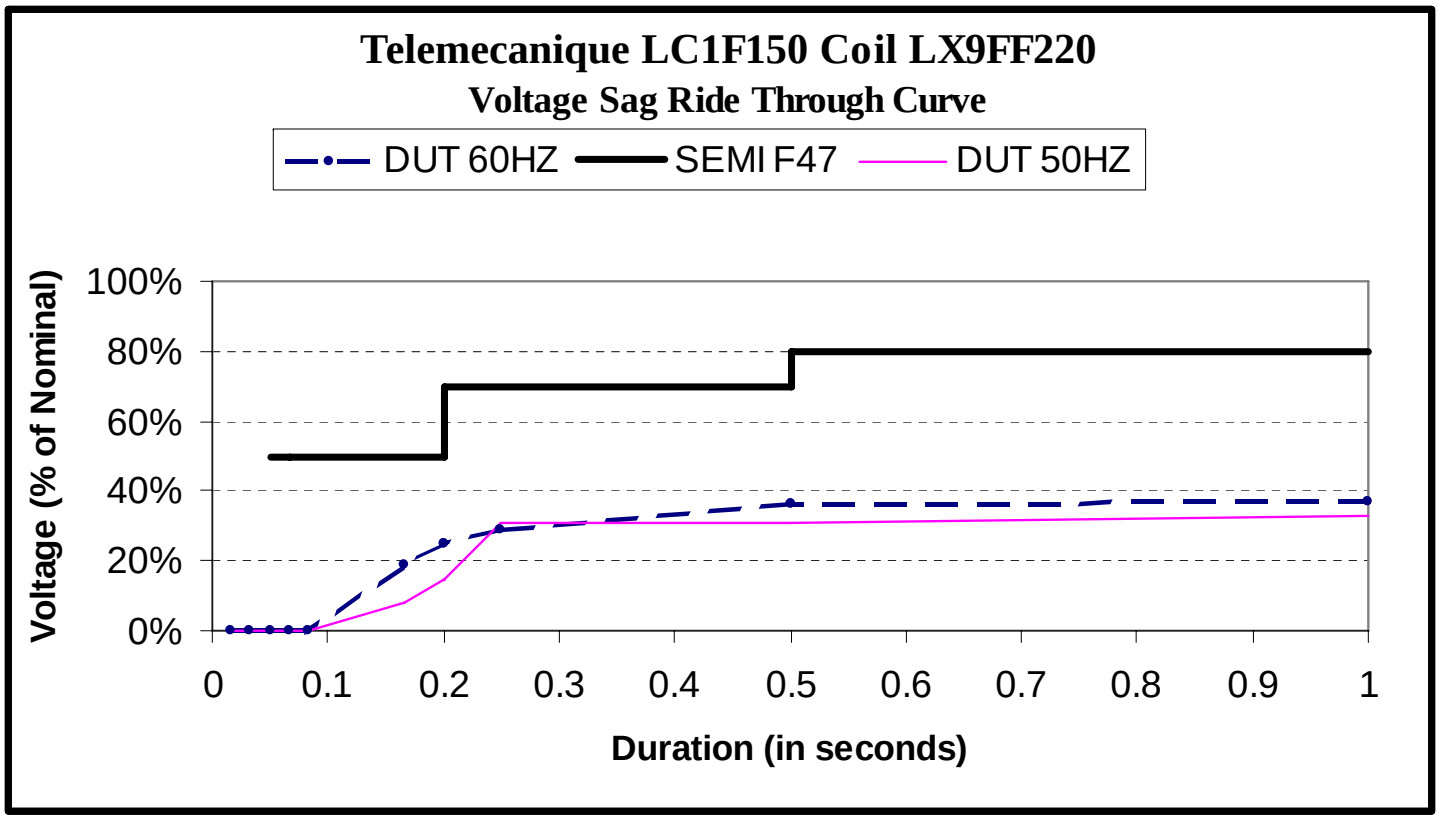
Example Robust Contactor



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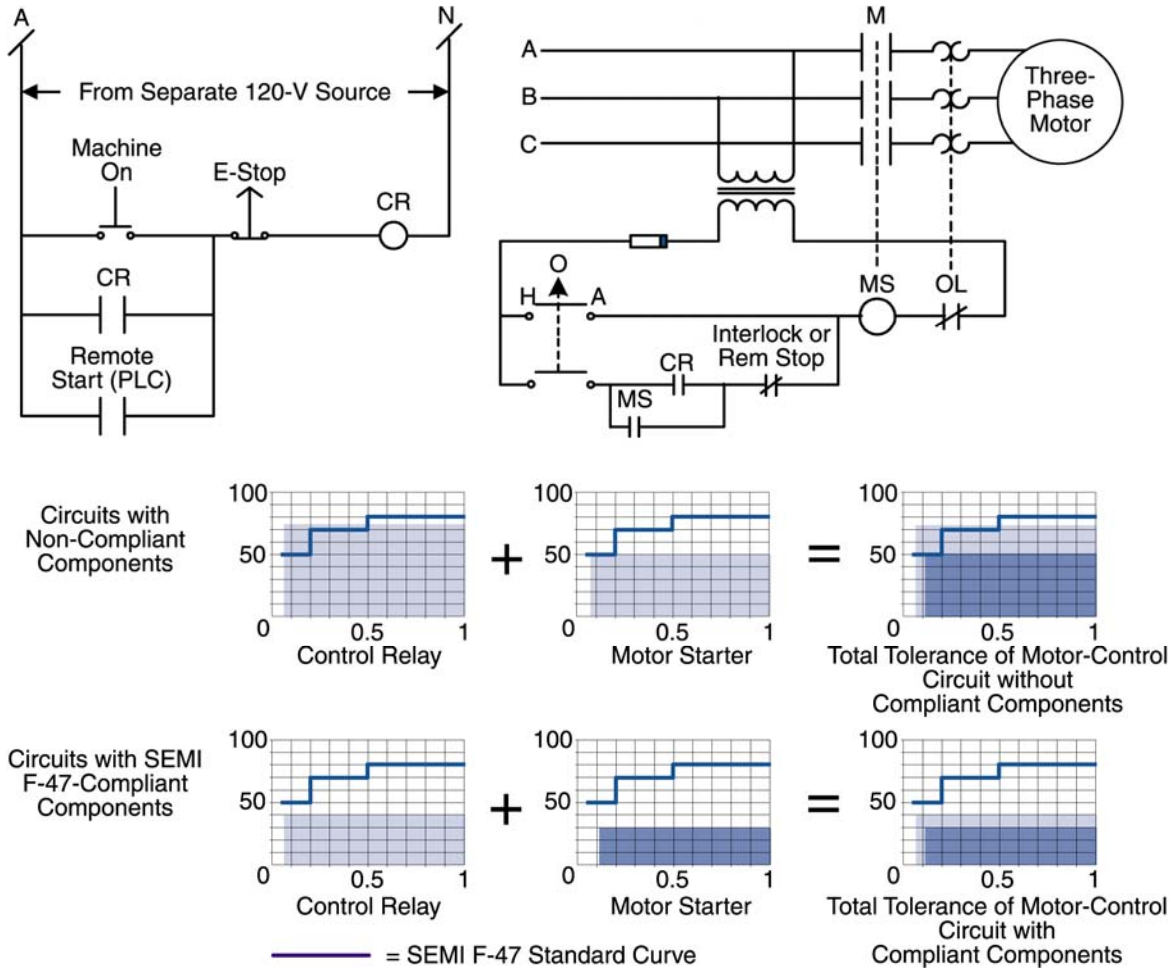
Example Voltage Sag Response of Motor Controls Based on Robustness of Components



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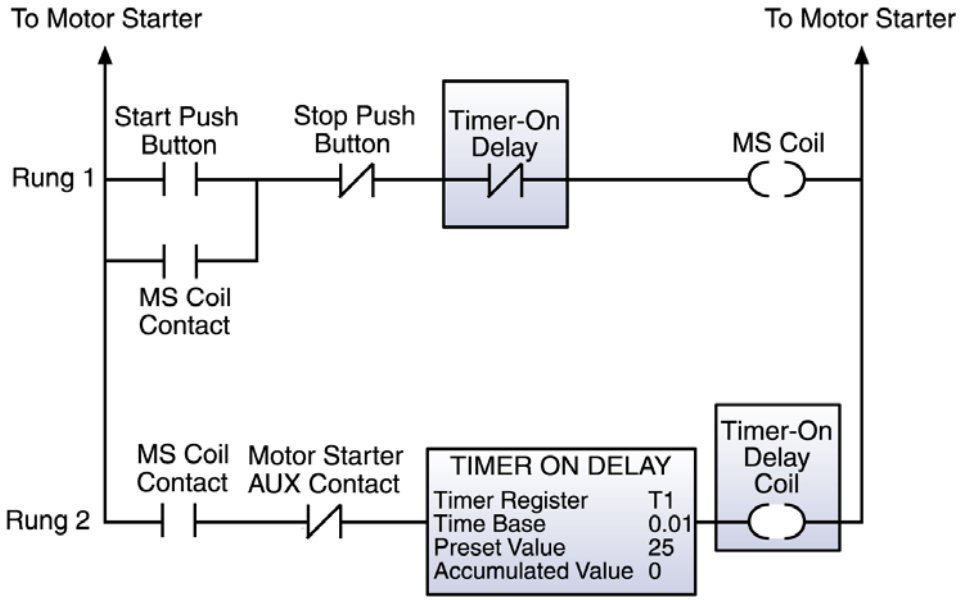
Method 3: Apply Custom Programming Techniques – Delay Filters

- **Delay filters** can be verify the presence of power and work as a “de-bounce” mechanism for when components drop out due to a voltage sag. The PLC motor-control circuit shown demonstrates how this method can be applied.
- The program is designed to detect whether the auxiliary contact is open for more than 250 milliseconds.
- If the contact is open for more than that preset time, then the “Timer On Delay Coil” in Rung 2 will be set and unlatch the previous rung to remove voltage from the motor starter.



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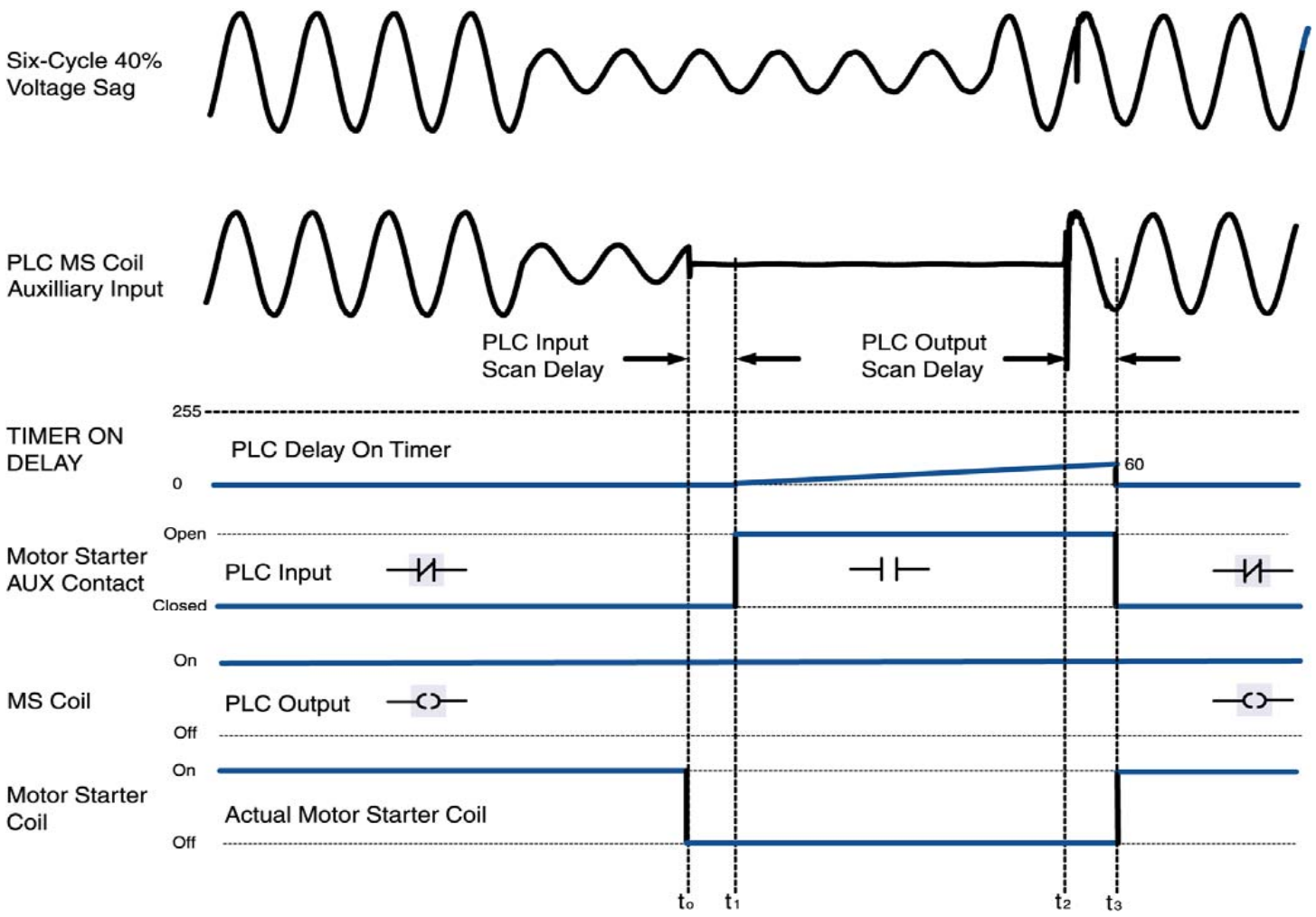
Method 3: Apply Custom Programming Techniques – Delay Filters



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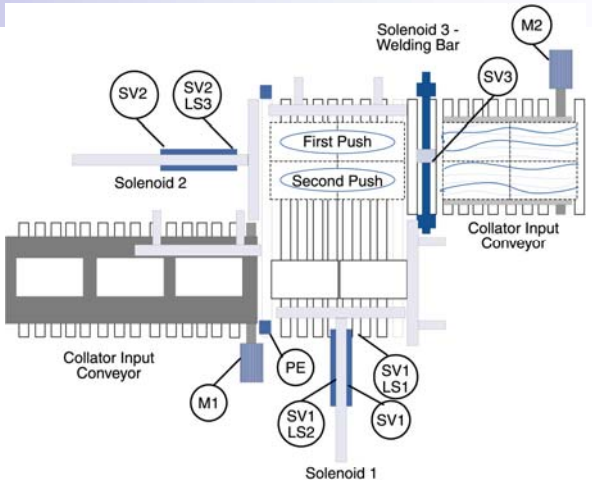
Method 3: Apply Custom Programming Techniques –State Machine Programming

- State Machine Programming is based on the idea that manufacturing processes are comprised of a number of steps with the goal of producing and moving a product.
- Therefore, machine-state programming keeps track of every sequential process state and associated variables by writing variables to non-volatile memory in the event power is lost.
- When power returns, the processing step number and variables can be recalled so that the machine can continue from where it stopped.



Machine-state programming uses coding, such as shown below, to store and retrieve data as needed.

1. IF PE_COUNT AND PUSH_COUNT EQUAL 0, THEN TURN M1 ON
2. WHEN PHOTO-EYE COUNT (PE_COUNT) EQUALS 3, STOP CONVEYOR
3. IF PE_COUNT EQUALS THREE AND M1 IS STOPPED, MOVE SOL1 TO LS1 AND INCREMENT PUSH_COUNT
4. IF PUSH_COUNT EQUALS 1 AND SOL1 IS HOME, TURN M1 ON
5. IF PE_COUNT IS EQUAL TO 6 AND M1 IS STOPPED, MOVE SOL1 TO LS2 AND INCREMENT PUSH_COUNT
6. IF PUSH_COUNT EQUALS 2 AND SOL1 IS HOME, MOVE SOL2 TO LS3 AND INCREMENT PUSH_COUNT
7. IF PUSH_COUNT EQUALS 3 AND SOL2 IS HOME, EXTEND SOLENOID 2 FOR 5 SECONDS
8. IF SOL3 TIMER IS DONE, TURN M2 ON FOR 5 SECONDS AND RESET ALL COUNTERS AND TIMERS (PE_COUNT AND PUSH_COUNT)

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Method 3: Apply Custom Programming Techniques – Programming Using Phase/Voltage Sensing Relay

- A phase monitor or voltage sensing relay, used in conjunction with programming, can also protect against the effects of voltage says.
- The relay contacts can be used to run a check on the system, retrieve past information stored in memory, or hold control parameters constant until the event is over.

Potential Sensing Devices For Voltage Sags

(Left to Right)

Phase Monitoring Relay

PQ Relay

"Original" PQ Relay (AC Ice Cube)

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Method 4 – Examine Configuration Settings

- A low-cost or perhaps no-cost method of increasing the tolerance of AC and DC motor drives to voltage sags is through software configuration settings.
- This method applies to all types of drives, including, but not limited to, AC pulse-width modulation (PWM), direct-current, AC-pulse, stepper, and servo drives.

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Method 4 – Examine Configuration Settings

- In most cases, drive manufacturers give users access to basic microprocessor program parameters so that the drive can be configured to work in the user's particular application.
- A drive's programming parameters associated with reducing the effect of voltage sags are seldom describes in one section of the user manual.

Functional Description:
Automatic Reset and Automatic Restart

Parameter	Parameter Description
Automatic Reset	This parameter allows the drive to automatically reset some fault conditions, such as DC link undervoltage or overvoltage, without the need for operator/user intervention. This feature is used in conjunction with Automatic Restart.
Automatic Restart	This parameter defines the method in which the drive automatically restarts after a fault condition is over. Automatic Restart operations may only be used as outlined in NFPA 79. Equipment damage and/or personal injury may result if the Automatic Restart parameter is used in an inappropriate application.
Automatic Restart Attempts	This parameter allows the user to program the number of times that the drive attempts to restart the motor after an undervoltage or other fault condition.
Automatic Restart Interval	This parameter is a user-specified time delay between the automatic restart attempts and the end of the fault condition.
Automatic Restart Time Delay	This parameter is a user-specified time delay between the end of the fault condition and an automatic restart.
Restart at User-Defined Frequency Setting	When the drive senses a DC link undervoltage condition, the drive shuts down the inverter, allowing the motor to coast. The motor is allowed to coast until the undervoltage condition ends. The drive then restarts the motor at a user-defined frequency setting. If the restart frequency is significantly higher or lower than the frequency of the motor, large inrush currents, torque, and speed transients could be induced on the motor (and load). The restart frequency setting, the acceleration rate, deceleration rate, current limit, and torque limit should be considered when using this feature.
Flying Restart	This parameter is similar to the parameter above with one major exception: Rather than restarting at a pre-defined frequency setting, the drive uses a search algorithm to determine the motor speed. Once the speed is recognized, the drive reaccelerates the motor to the desired operating point. The odds of the motor and load experiencing extreme current and torque transients are greatly reduced.

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Method 4 – Examine Configuration Settings

Functional Description: Motor Load Control

Parameter	Parameter Description
Kinetic Buffering	When the drive senses a DC link low-voltage condition, the drive uses the combined motor-load inertial energy to maintain a factory-programmed DC link voltage inside the drive by applying a braking force to the motor. This feature does not create a potential for extreme current or torque transients.
Motor Voltage Compensation	When the drive senses a DC link low-voltage condition, the drive's controller changes the inverter firing timing sequences to compensate for a reduced DC link voltage. The objective is to maintain as close as possible the desired output voltage for operating the motor and load.
Controlled Deceleration and Acceleration	When the drive senses a DC link undervoltage condition, the drive begins to decelerate the motor at a user-defined rate. When the undervoltage condition ends, the drive reaccelerates the motor back to the desired operating point. This feature is often used in processes with multiple drives operating in succession, where all drives are expected to operate in unison to maintain process quality. This feature works well for common DC bus drive systems.

Motor-load control uses the motor's inertia or controlled acceleration/deceleration to ride-through voltage sags.

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Method 4 – Examine Configuration Settings

Functional Description: Phase Loss and DC Link Undervoltage

Parameter	Parameter Description
Input Phase Loss	The input phase-loss-detection circuit monitors either the input phases or DC bus current ripple and activates when one of the input phases is lost. In some drives, an input-phase loss alarm will be generated if the duration of the phase loss is greater than the input Phase Loss Delay setting.
Input Phase Loss Delay	This parameter controls the delay time in which an input phase loss must be present before a fault is generated. If the input phase returns to nominal before the delay time, a fault will not be generated.
DC Bus Undervoltage Limit or Undervoltage-Detection Level	Some drive manufacturers allow users to change the DC bus undervoltage trip point. By lowering the trip point, drives and processes may ride through longer and deeper voltage sags without interrupting production. This feature may be standard or may require a drive software upgrade from the manufacturer.
DC Bus Undervoltage Delay	This parameter allows the user to set a time delay for a DC bus undervoltage fault. If the duration of the undervoltage exceeds the delay time, the drive faults. Otherwise, the drive continues normal operation.

Detecting a loss of phase enables a drive to delay a fault condition and ride through the loss of phase. The DC link undervoltage trip point can be adjusted to enable a drive to ride through sags.

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Method 4 – Examine Configuration Settings

Functional Description: Limits

Parameter	Parameter Description
Acceleration, Deceleration, Current Limit, and Torque Limit	These parameters are especially important after a sag ends and the drive attempts to recover. Inappropriate settings may cause the drive to trip or may not allow the process to recover.

Rate of acceleration, rate of deceleration, current limit, and torque limit are parameters that affect the way a drive attempts to recover after a voltage sag.

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Example Settings Rockwell Power Flex 70 & 700

- Conducted SEMI F47 compliance Testing on Power Flex 70 and 700 Series drives in EPRI Lab.
- Drives have built in parameters that can be used to improve voltage sag performance.
- Drives loaded to 100%

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PowerFlex 70 and 700 Ride-Through Parameters

- Two distinct modes of operation, ASD, to help with “Ride-Through”
  - “Inertia ride-through” or “Decel” mode
    - ASD attempts to maintain the DC bus voltage at certain level by regenerating power from load
    - More output speed droop relative to “Continue Mode”
    - For a given sag duration, DC bus voltage will not droop as much as “Continue” mode
  - “Continue Mode”
    - For a given sag duration, larger DC bus voltage droop than “Decel” mode
    - Less output speed droop relative to “Decel” mode
    - Drive is allowed to run at set-speed and load
    - Depending on duration of sag and the level of bus voltage droop
      - May result “undervoltage” fault
    - Increased output current to maintain load
      - ASD may trip on “Overload”

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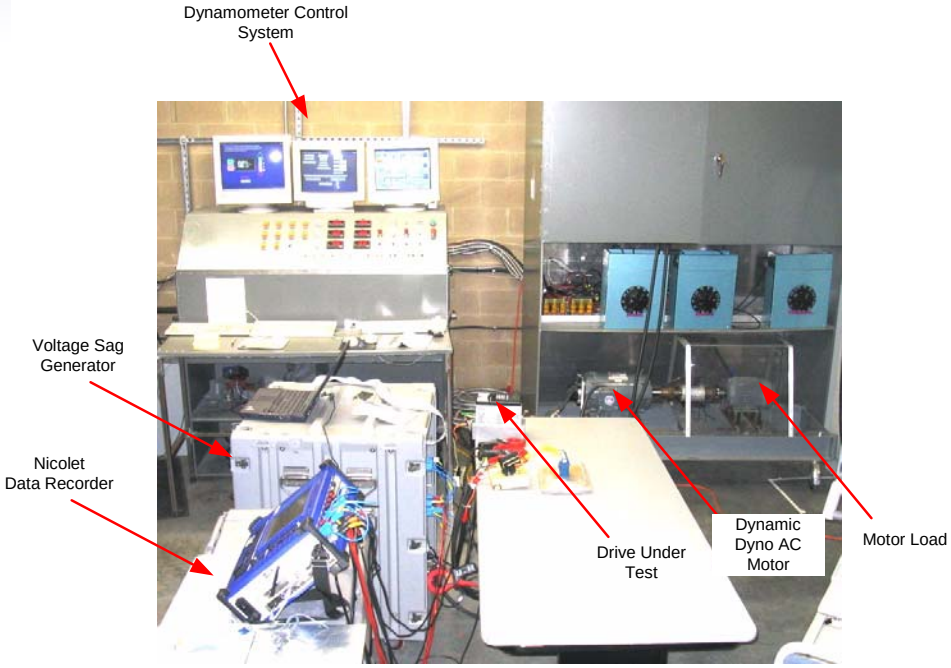
Typical Drive Test Setup

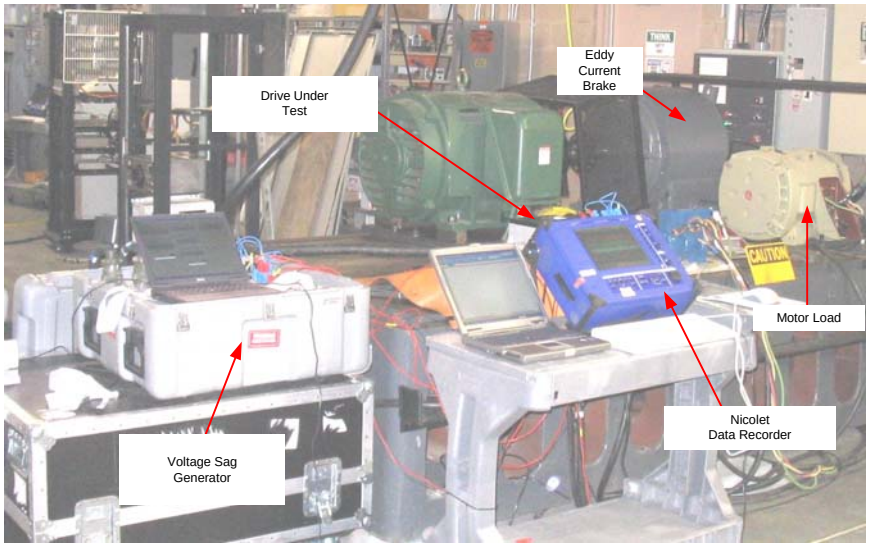


Test Setup for Smaller Drives

(2 to 15 HP)

Test Setup for Larger Drives

(20 to 150HP)



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Parameter Setup

PowerFlex® 70 Drive Parameters Important for Power Quality Robustness

Par No.	Name and Description	Setting	Related Par.	SEMI F47 Setup Considerations
169	**[Flying Start En]** Enables/Disables the function which reconnects to a spinning motor at actual RPM when a start command is issued.	**Default:** 0 "Disabled" **Options:** 0 "Disabled" 1 "Enabled"	170	If drive experiences an overcurrent or undervoltage fault during a voltage sag event, then this parameter can allow it to catch the spinning motor if Parameter 174 [Auto Rstrt Tries] is set to any value except default.
174	**[Auto Rstrt Tries]** Sets the maximum number of times the drive attempts to reset a fault and restart.	**Default:** 0 **Options:** Min/Max: 0/9 Units: 1	175	Must have this parameter set to something other than default in order to reset an overcurrent fault or undervoltage fault and allow the drive to catch the spinning motor.
184	**[Power Loss Mode]** Sets the reaction to a loss of input power. Power loss is recognized when: • DC Bus Voltage is <= 73% of [DC Bus Memory] and [Power Loss Mode] is set to "Coast" • DC Bus Voltage is <= 82% of [DC Bus Memory] and [Power Loss Mode] is set to "Decel"	**Default:** 0 "Coast" **Options:** 0 "Coast" 1 "Decel" **2 "Continue"**	013 185	Set to a value of "2" for continuous speed operation. The drive will work to maintain speed by drawing more current during the voltage sag.
185	**[Power Loss Time]** Sets the time that the drive will remain in power loss mode before a fault is issued.	**Default:** 0.5 Sec **Options:** Min/Max: 0.0/60.0 Sec Units: 0.1	184	Default Setting should be sufficient for SEMI F47 duration voltage sags.

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Test Result – Default Configuration: P184=0

SEMI F47 Test - Adjustable Speed Drive Data Sheet

Test Designator:	**RA_ASD_1**	Notes:	FW 2.009
Model:	20AD8P0A3AYYNDNN		Power Flex 70 Control Board
Specs:	Power Flex 70, 5HP		Default Configuration
Nom. Voltage:	480Vac		Parameter 184 Decel Set to "0"
Nom. Speed (rpm):	1730		
Freq.(Hz)	60		
Date:	7/19/2005		
Tester:	Dennis Turner		FLA=6.5

Duration			With Line Reactor				Without Line Reactor			
Sec.	Cycles 60Hz	SEMI F47 Standard Test Points	Min. Speed (rpm)	Min. Speed % of Nom.	Automatic Restart	Speed Remain above 95%	Min. Speed (rpm)	Min. Speed % of Nom.	Automatic Restart	Speed Remain above 95%
1	60.0	80%	1696	98%	Yes	Yes	1704	98%	Yes	Yes
0.5	30.0	70%	1684	97%	Yes	Yes	1692	98%	Yes	Yes
0.2	12.0	50%	525	30%	Yes	No	736	43%	Yes	No
0.05	3.0	50%	530	31%	Yes	No	647	37%	Yes	No

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Test Result – Default Configuration: P184=1 “Decel” Mode

SEMI F47 Test - Adjustable Speed Drive Data Sheet

Test Designator:	**RA_ASD_1**	Notes:	FW 2.009
Model:	20AD8P0A3AYYNDNN		Power Flex 70 Control Board
Specs:	Power Flex 70, 5HP		Default Configuration
Nom. Voltage:	480Vac		Parameter 184 Decel Set to "1"
Nom. Speed (rpm):	1730		
Freq.(Hz)	60		
Date:	7/19/2005		FLA=6.5
Tester:	Dennis Turner		

Duration			With Line Reactor				Without Line Reactor			
Sec.	Cycles 60Hz	SEMI F47 Standard Test Points	Min. Speed (rpm)	Min. Speed % of Nom.	Automatic Restart	Speed Remain above 95%	Min. Speed (rpm)	Min. Speed % of Nom.	Automatic Restart	Speed Remain above 95%
1	60.0	80%	1699	98%	Yes	Yes	1708	99%	Yes	Yes
0.5	30.0	70%	1328	77%	Yes	No	1232	71%	Yes	No
0.2	12.0	50%	1349	78%	Yes	No	1290	75%	Yes	No
0.05	3.0	50%	1622	94%	Yes	No	1618	94%	Yes	No

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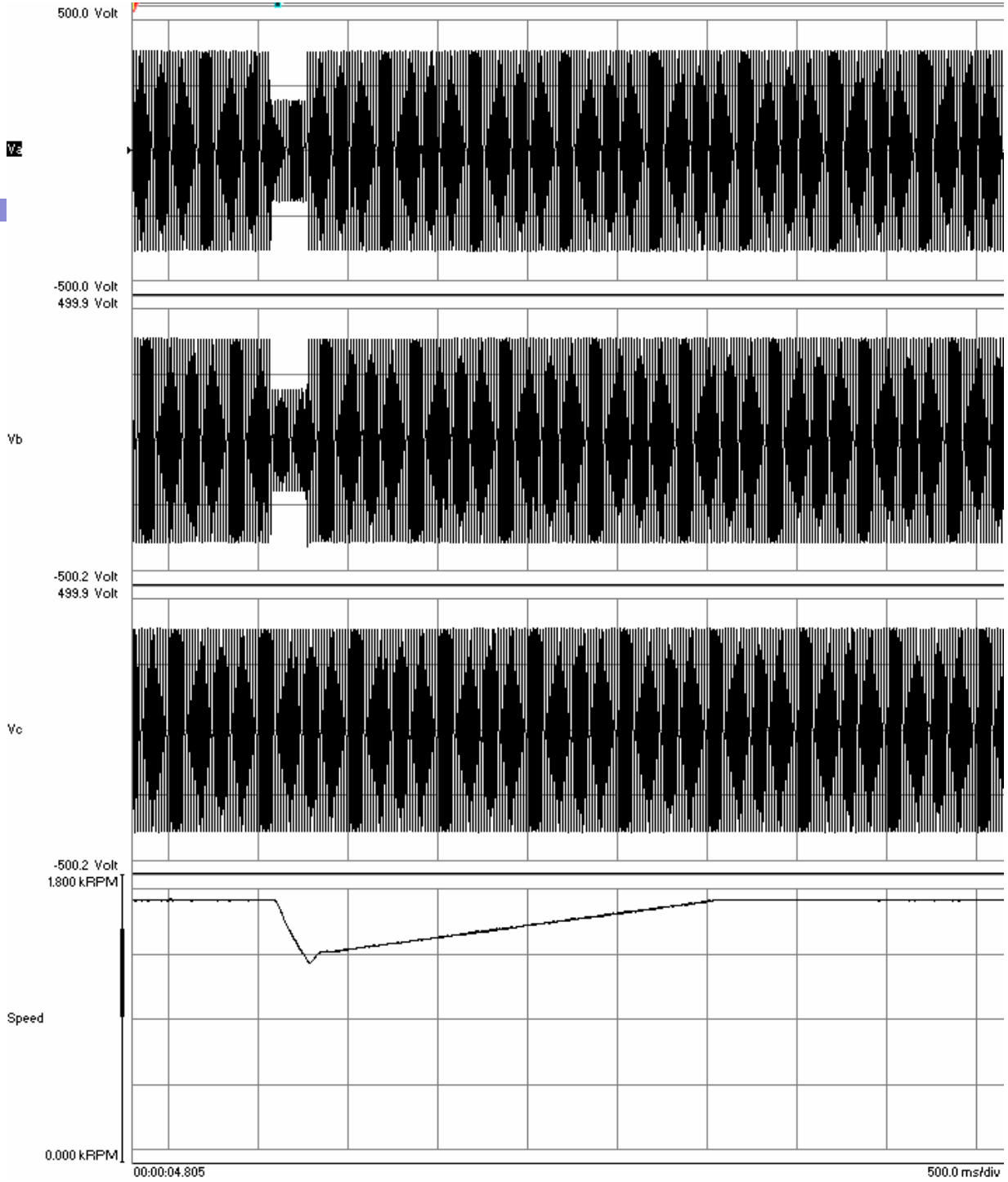
Example Response

- Example Worst Case Speed Deviation: 12 Cycles, 50% Vab without Line Reactor
- **Set for P184= “DECEL” mode**



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Test Result – Default Configuration: P184=2 "Continue" Mode

SEMI F47 Test - Adjustable Speed Drive Data Sheet

Test Designator:	**RA_ASD_2**
Model:	20BD011A0AYNANCO
Specs:	Power Flex 700, 5HP
Nom. Voltage:	480Vac
Nom. Speed (rpm):	1730
Freq.(Hz)	60
Date:	7/19/2005
Tester:	Dennis Turner

Notes:
FW 4.002, Vector Control
Power Flex 70 Control Board
Default Configuration
Parameter 184 Set to "2" Cont

Duration			With Line Reactor				Without Line Reactor			
Sec.	Cycles 60Hz	SEMI F47 Standard Test Points	Min. Speed (rpm)	Min. Speed % of Nom.	Automatic Restart	Speed Remain above 95%	Min. Speed (rpm)	Min. Speed % of Nom.	Automatic Restart	Speed Remain above 95%
1	60.0	80%	1694	98%	Yes	Yes	1703	98%	Yes	Yes
0.5	30.0	70%	1681	97%	Yes	Yes	1694	98%	Yes	Yes
0.2	12.0	50%	1627	94%	Yes	No	1662	96%	Yes	Yes
0.05	3.0	50%	1655	96%	Yes	Yes	1677	97%	Yes	Yes

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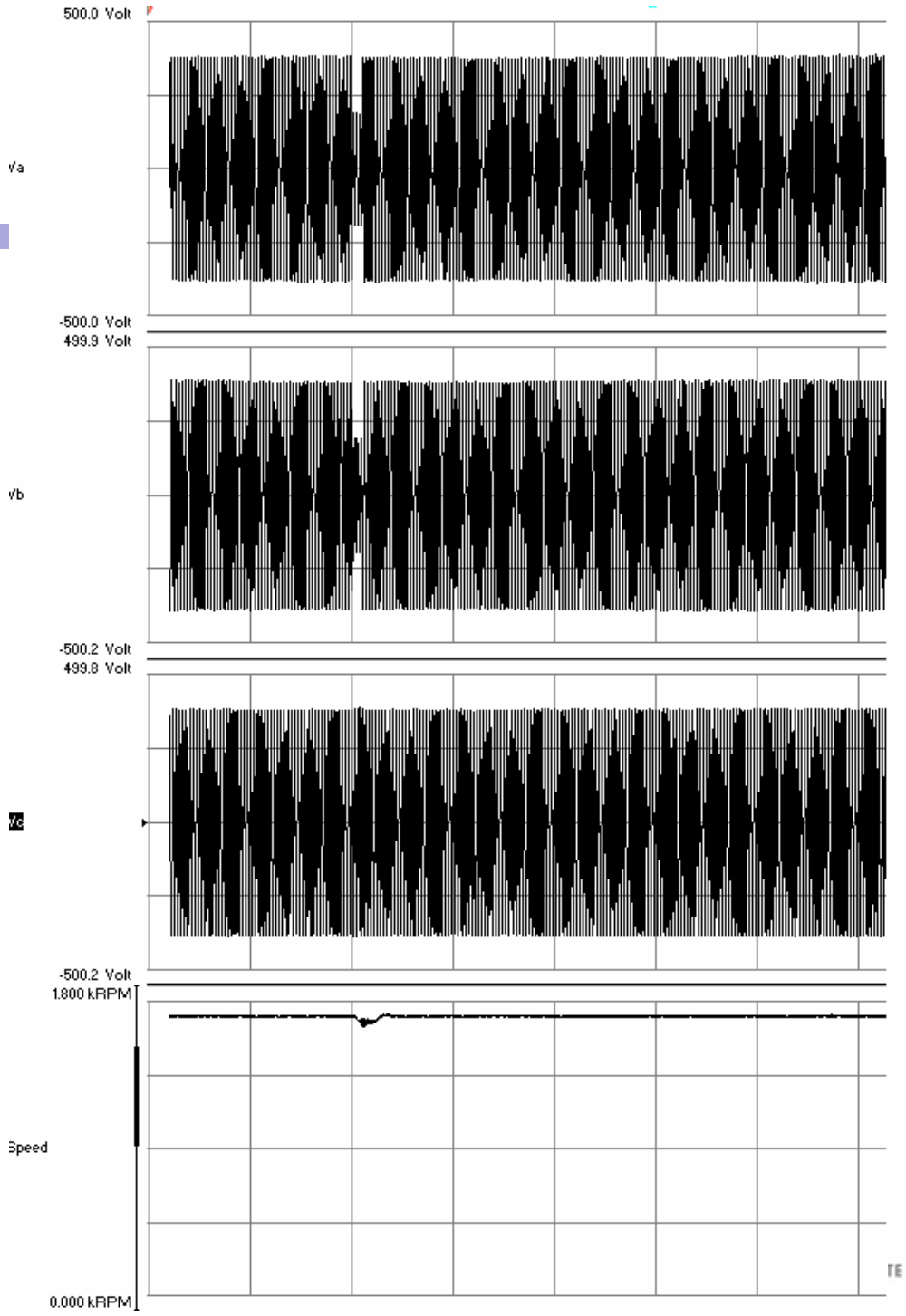
Example Response

- Example Worst Case Speed Deviation: 12 Cycles, 50% Vab without Line Reactor
- **Set for P184= “Continue” mode**



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Schneider-Toshiba Altivar 61 & 71 Drives

- This newer drive series was recently tested as a part of the EPRI PQ Star SEMI F47 compliance program.
- Drives were found to pass the standard.
- Certification Relates to multiple drive models manufactured from same control platform
  - STI Altivar 61 and 71
  - ELIN >pDRIVE<
  - MX ECO and MX PRO

Altivar 61 and 71 Series Drives

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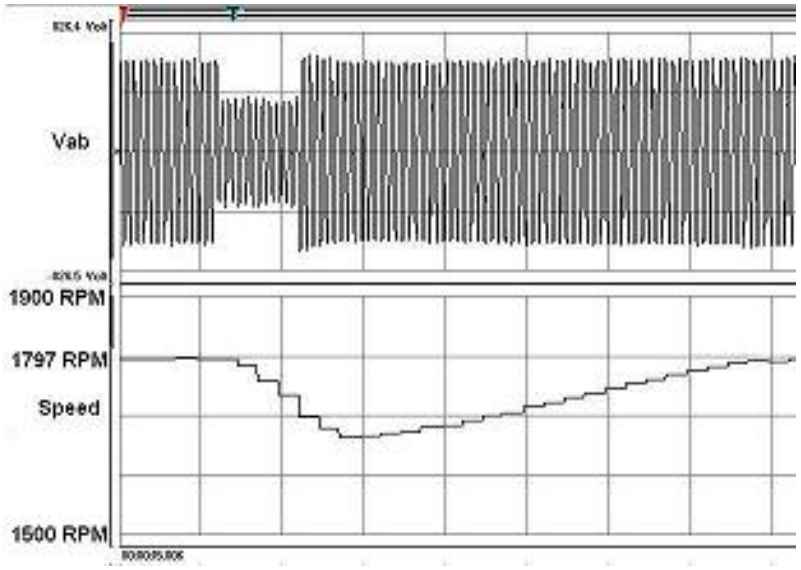
Schneider-Toshiba Altivar 61 & 71 Drives

- The drives were able to pass the SEMI F47 testing requirements when configured properly.
- Prameters such as "Input Phase Loss", "Catch on the Fly", and Undervoltage Timeout (UV Timeout) had to be set.
- The dynamic torque profile was test to follow the "High Torque A" and the default slip compensation was set to 100%.



Parameter	Setting
Input Phase Loss	Ignore
Catch on Fly	Yes
UV Timeout	3 sec
UV Prevention	DC maintain
Slip Compensation	100% (default)
Dynamic Torque	High Torque A

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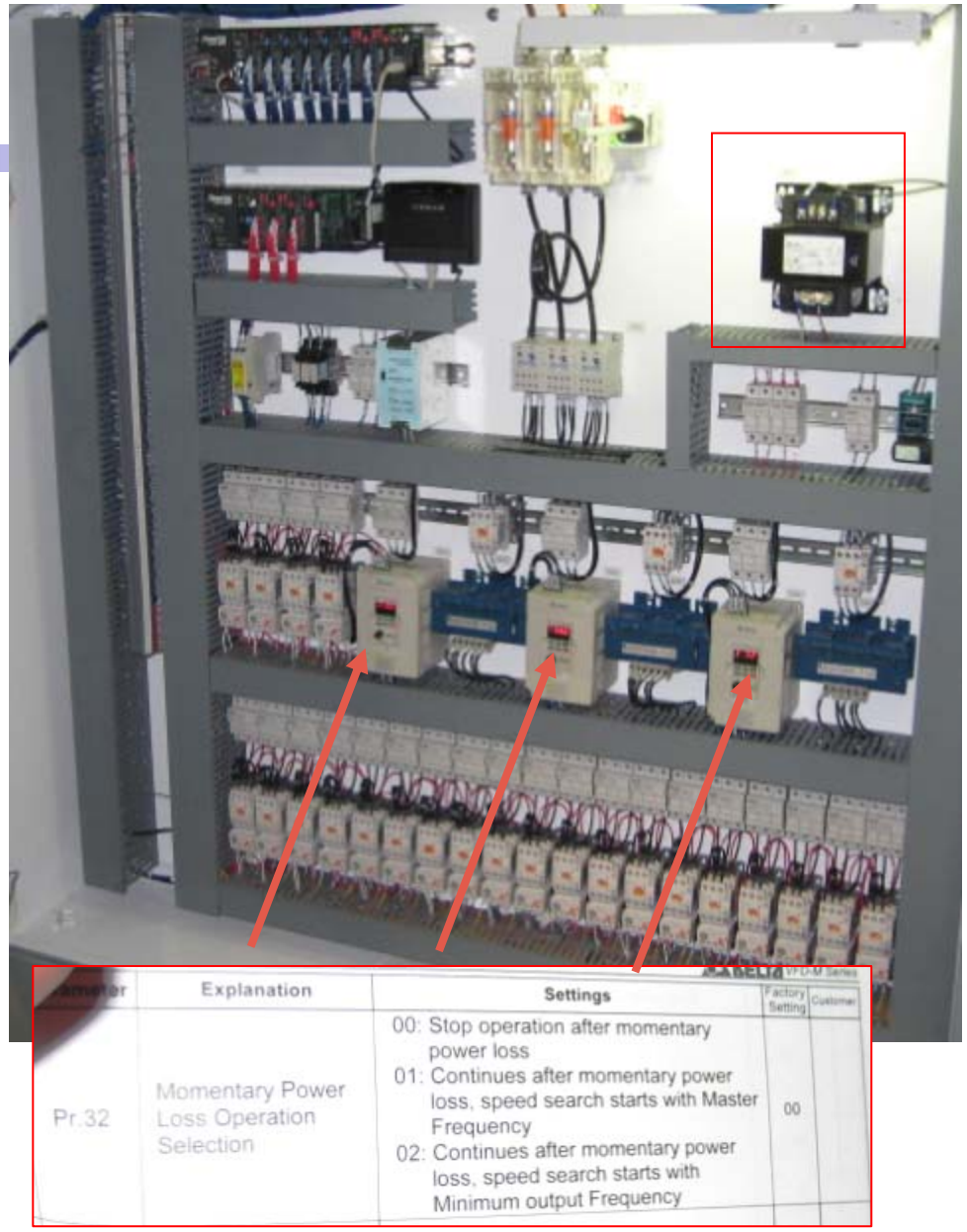
Example System with Drives

- 750VA 480/120 CPT
- DC Powered PLC
- AC and DC I/O
- Drives have line reactors
- Drives Have Restart on Power Loss Parameters
  - MUST CONSIDER SAFETY ISSUES WITH AUTO RESTART
- Could be robust to 50% of nominal sag without conditioning
- Solution
  - Option 1:
    - 750VA MiniDySC on 120Vac controls $1320
    - www.sagshappen.com
  - Option 2:
    - 1kVA 480 3-phase, 120 Vac output Power Ride RTD
    - $1,180


Explanation
Settings
Factory Setting
Customer
Pr.32
Momentary Power Loss Operation Selection
00: Stop operation after momentary power loss
01: Continues after momentary power loss, speed search starts with Master Frequency
02: Continues after momentary power loss, speed search starts with Minimum output Frequency
00

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Method 5 – Select Appropriate Trip Curves for Circuit Breakers

- Some equipment, especially equipment with AC-to-DC converters, may respond to a voltage sag by drawing inrush current when the voltage supply returns to normal.
- During a voltage sag, the AC-to-DC converter capacitors discharge. At the end of the sag, the sudden presence of a full voltage causes the discharged capacitors to rapidly recharge.
- The magnitude of this inrush of current depends on the depth and duration of the voltage sag. The resulting current transient may be large enough to trip circuit breakers that have a quick response time.
- Process machines with any type of AC-to-DC converter—such as DC power supplies, AC or DC variable-speed drives, and servo drives—can not only cause such transients but may also be susceptible to breaker trips caused by the transients.

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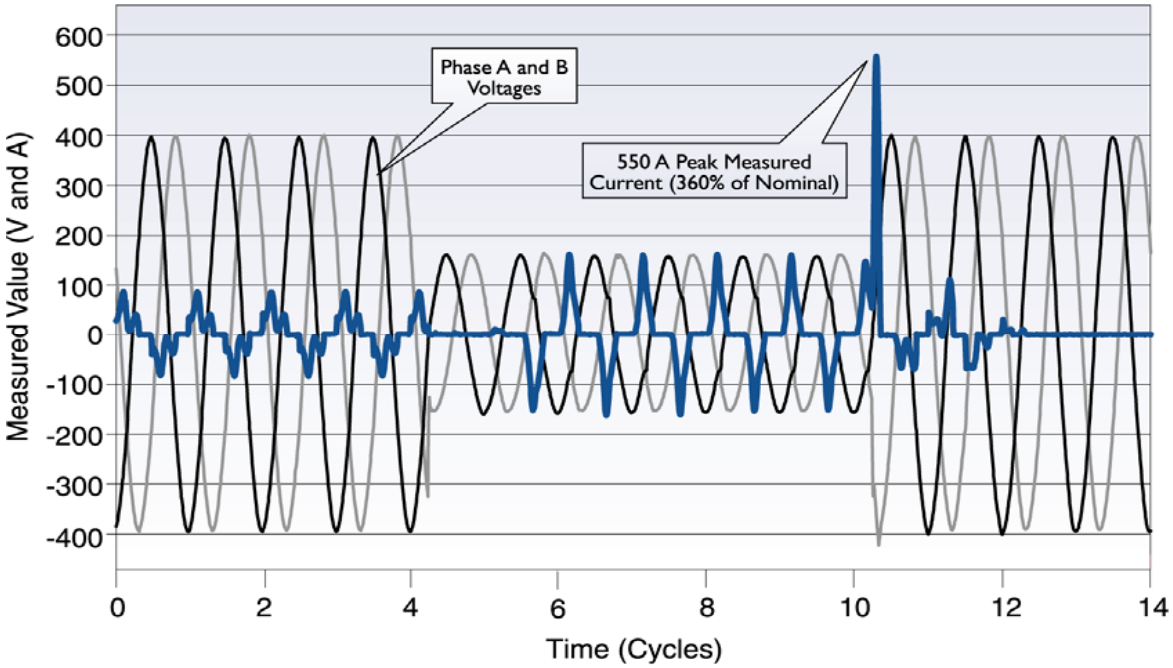
Method 5 – Select Appropriate Trip Curves for Circuit Breakers



This voltage sag to 40% of nominal voltage caused the capacitors in a variable-frequency drive to discharge. When the input voltage returned to normal after six cycles, the capacitors suddenly charged, causing an inrush current transient that peaked at 360% of the normal operating current.

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Method 5 – Select Appropriate Trip Curves for Circuit Breakers – Case Study

- Power Supply design was modified to lower the DC bus undervoltage trip point of the unit after failing initial SEMI F47 testing.
- SEMI F47 Tests were again conducted after the modifications.
- Circuit Breaker was found to then trip, leading to non-compliance of the unit as a whole.
- The Unit was fitted with a new circuit breaker of the same amperage value, without an instantaneous trip.
- Unit then passed SEMI F47 tests.

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Method 5 – Select Appropriate Trip Curves for Circuit Breakers – Case Study

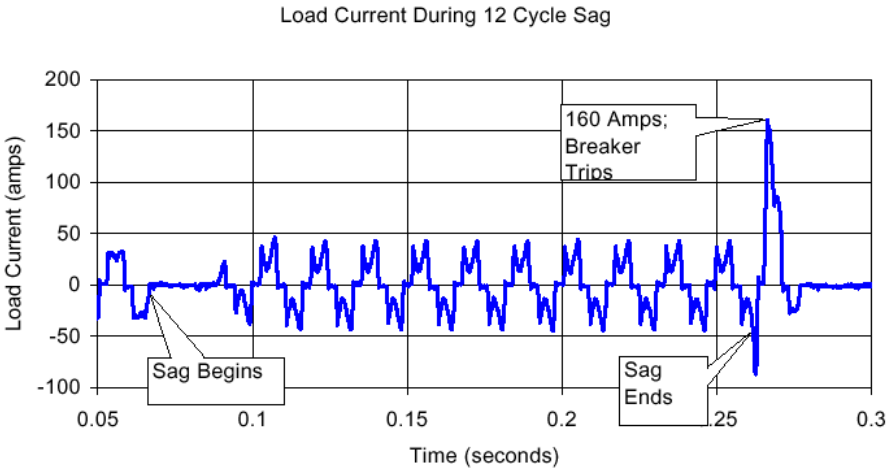
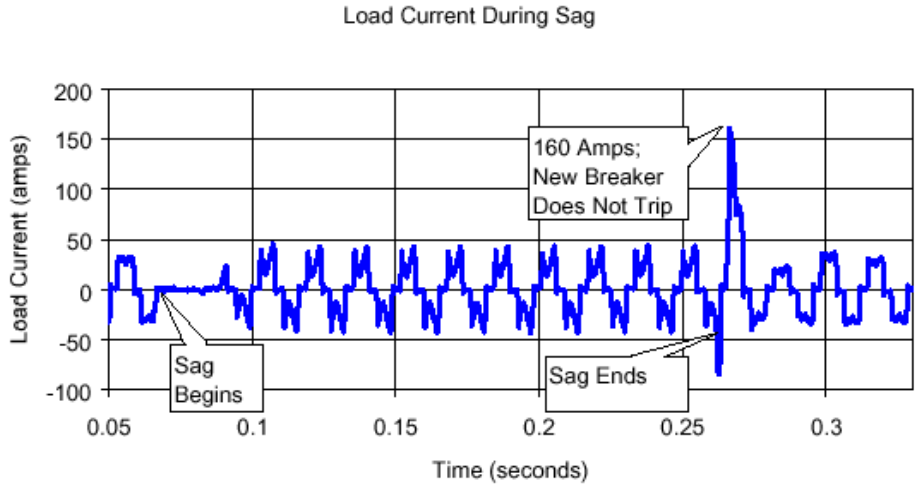


Figure 2. Load Current During Sag



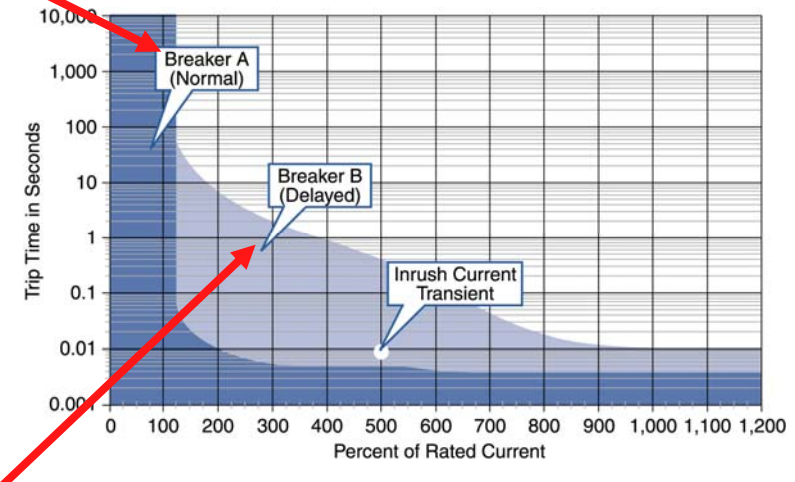


Figure 4. Response of New Circuit Breaker

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Other Considerations

- Make sure the device rated voltage matches the nominal voltage. Mismatches can lead to higher voltage sag sensitivities (for example 208Vac fed to 230Vac rated component).
- Consider Subsystem performance. Vendor subsystems must be robust for the entire system to be robust. Otherwise, power conditioning may be required for the subsystem.
- Consolidate Control Power Sources. This will make the implementation of any required power conditioner scheme much simpler and cost effective.
- Use a targeted voltage conditioning approach as the last resort. Apply Batteryless power conditioner devices where possible (next session)

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Case Study Magnet Wire Plant Resolves PQ Issues

Introduction

- A magnet wire plant experienced voltage-sag-related process upsets on several of its wire manufacturing lines.
- The plant load was approximately 5 MVA and was fed from three 2-MVA transformers.
- In addition to the wire lines, other important process sections of the plant include a rod mill and enamel, lubricant, and mechanical-room systems.
- In order to decrease the susceptibility of the plant to power quality (PQ) disturbances, the local utility supplying the magnet wire plant requested that EPRI provide a detailed PQ audit.
- The PQ audit revealed that several controls were susceptible to power quality disturbances.

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Background (1)

- The need to provide reliable power with a steady voltage and frequency has been recognized since the inception of the electric utility industry.
- Voltage sags are the most important power quality variation affecting equipment because statistically they are the most frequent.
  - This was determined in the EPRI Distribution Power Quality (DPQ) study.
  - Lightning strikes, animals, fires, equipment failure, auto and construction accidents, and wind are some of the causes for power system faults.

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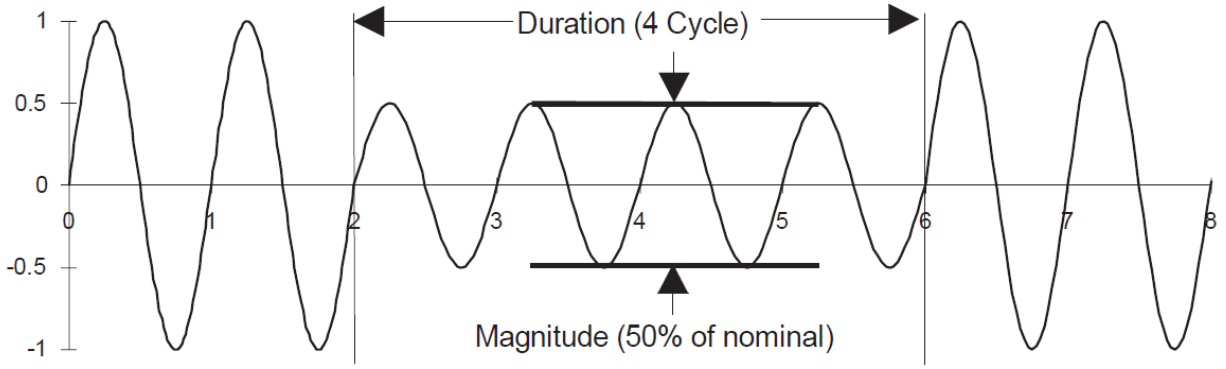
Background (2)

- Voltage sags, a decrease in RMS voltage at the power frequency for durations of 0.5 cycles to 1 minute, and interruptions are caused by faults (short circuits) on the power system.
- The location of the fault and the power system configuration determine the severity of voltage sags, while the power system protection scheme usually determines the duration.
- Below is a voltage sag characterized by a duration of four cycles and a depth of 50%.



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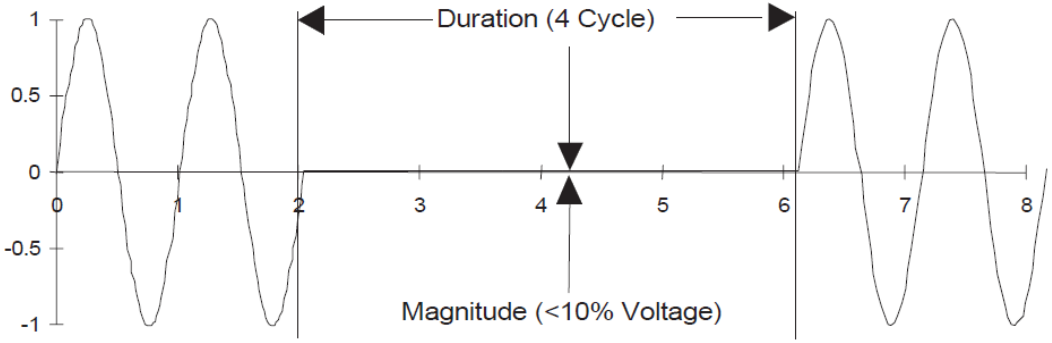
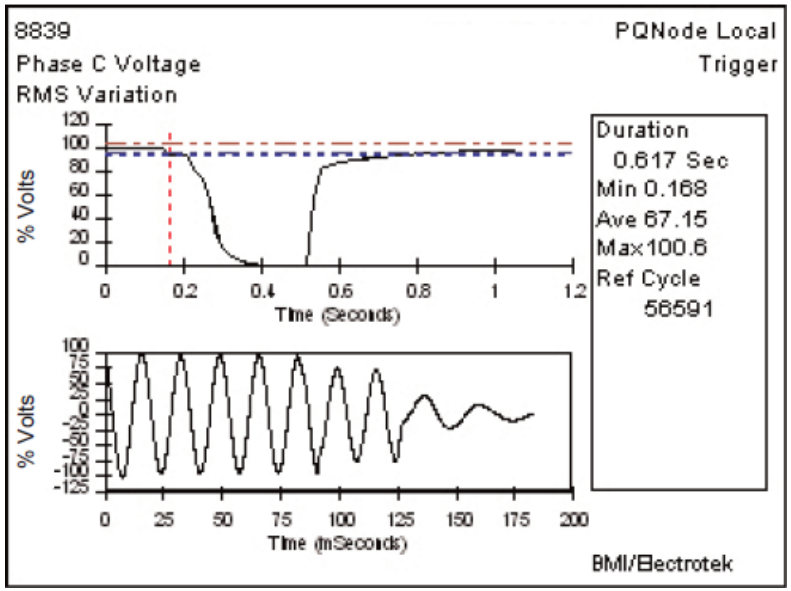
Background (3)

- In the United States, a typical voltage sag is:
  - 6–10 cycles (100–167 milliseconds) in duration
  - Greater than 60% to 70% of nominal voltage in magnitude
  - Typically single-phase and appears in either one or two phases inside the plant.
- A momentary interruption occurs when the supply voltage decreases to less than 10% of nominal for a period of time not to exceed 1 minute.
  - These Interruptions are measured by duration since the voltage magnitude is always less than 10% of nominal.
  - Typical duration for interruptions is 30–120 cycles (0.5–2.0 seconds) and depends on recloser fault clearing time.



Typical Interruption Event Waveform

Actual Interruption Waveform and RMS Plot



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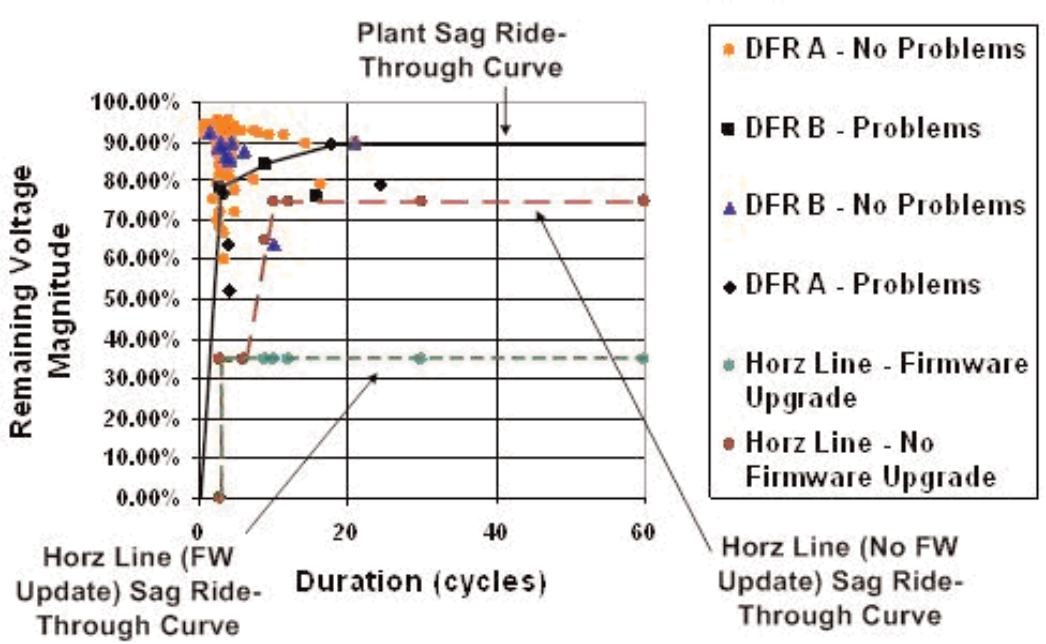
Background (3)

- The magnet wire plant is supplied by a local substation that is fed from a tapped 115-kV transmission line jointly owned by two other utilities.
- The “scatter plot” below shows the voltage sags experienced by the plant from April 2000 to October 2001.
  - It is a composite of single-phase data from the 115-kV line and the plant’s incoming transformer voltage.
  - The PQ data was recorded by two digital fault recorders (A and B).
- Analysis of the data reveals that the magnet wire plant had reported upsets for voltage sags ranging from 3 cycles, 78% of nominal voltage to 18 cycles, 89% of nominal.

Actual Interruption Waveform and RMS Plot



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Plant Power Quality Assessment (1)

- The magnet wire plant utilizes programmable logic controllers (PLC) and AC drive technology as the backbone of the control systems.
- Typically, the characteristics of a robust PLC-based control system are:
  - DC-powered PLC power supply
  - DC-powered input/output (I/O) and control power
  - Robust AC drives
- A scoring system was used to evaluate the susceptibility of various manufacturing lines in the plant to power quality disturbances.

Summary of Power Quality Attributes for PLCs and AC Drives

Equipment	Power Quality Influences			
PLC	DC-Powered Rack Power Supply Enhances PQ Robustness (+1)	AC-Powered Rack Power Supply Decreases PQ Robustness (–1)	DC Powered I/O Enhances PQ Robustness (+1)	AC Powered I/O Decreases PQ Robustness (–1)
AC Drive	DC Bus Trip Level Set Low (50% Range) Enhances PQ Robustness (+2)	DC Bus Trip Level Set High (80% Range) Decreases PQ Robustness (–2)	Lightly Loaded AC Drive Enhances PQ Robustness (+1)	Heavily Loaded AC Drive Decreases PQ Robustness (–1)

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Plant Power Quality Assessment (2)

- Based on this summary table, it is apparent that the magnet wire plant uses a large number of drives.
- The PQ audit revealed that several PLCs and I/Os are AC powered, making them susceptible to voltage sag events.

System	Plant Area	Number of Lines	PLCs (total per system)	AC Drives (total per system)
Process Systems	Rod Mill	1	3	None
	Horizontal Oven Lines	56	70	352
	Vertical Oven Lines	12	16	72
	Enamel System	1	1	None
	Lubricant System	1	1	None
	Machine Room			2
Total			91	426

PLC Cabinet Powered by AC with a Mixture of AC and DC I/O

DC-Powered PLC and I/O with Four Motor Drives

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Plant Power Quality Assessment (3)

- The weighted calculations for each process area's PQ performance is scored based on the system discussed earlier.
- Scores of zero or less are susceptible to voltage sags and all others have some degree of robustness

Weighted Score Assessment of Various Manufacturing Lines in Magnet Wire Plant

Plant Area	Number of Lines	PLCs				AC Drives		Plant Area PQ Score
		AC I/O?	DC I/O?	AC PLC RackPower Supply?	DC PLC Rack Power Supply?	DC Bus Trip Level (80% Range)	DC Bus Trip Level (50% Range)	Score>0 means robust Score<=0 means susceptible
Rod Mill	1	No	Yes +1	Yes –1	No	Other DC drives used	Other DC drives used	0
Horizontal Oven Lines	56	No	Yes +1	No	Yes +1	Yes –2	No	0
Vertical Oven Lines	12	No	Yes +1	No	Yes +1	Yes –2	No	0
Enamel System	1	Yes –1	Yes +1	Yes –1	No	Drives not used	Drives not used	–1
Lubricant System	1	Yes –1	Yes +1	Yes –1	No	Drives not used	Drives not used	–1
Mechanical Room PLC	1	Yes –1	Yes +1	Yes –1	No	Yes –2	No	–3

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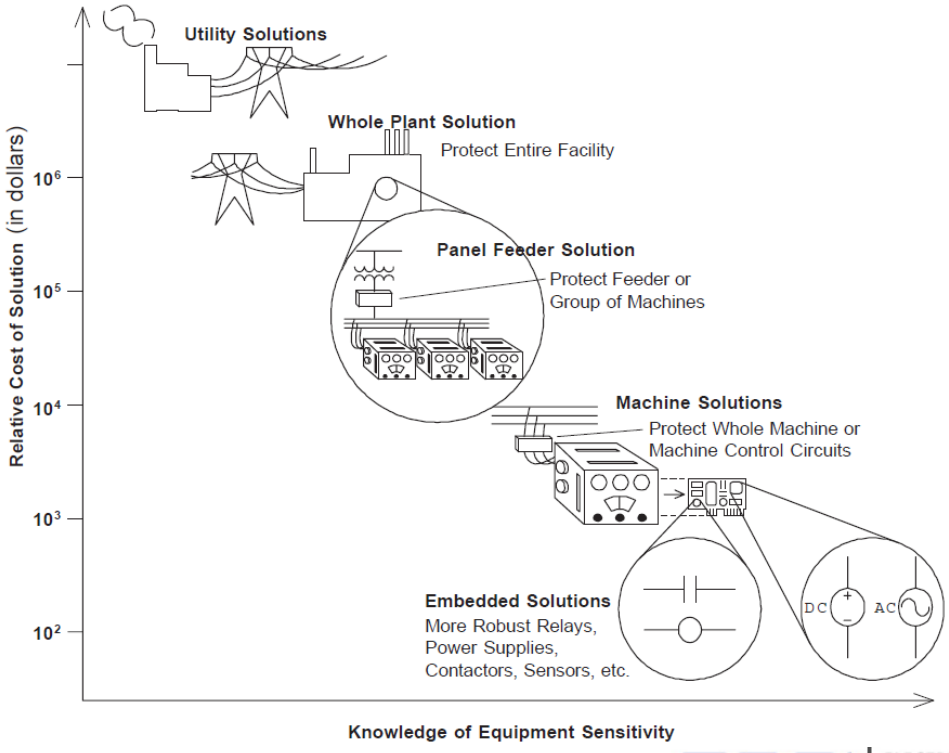
Recommendations for Hardening Magnet Wire Plant to Power Quality Disturbances

- A detailed assessment and inspection of various electrical controls in the magnet wire plant revealed that several manufacturing lines were susceptible to power quality disturbances.
- The audit recommended all possible options with particular emphasis on low-cost modifications by changing AC drive firmware and adding small power conditioners to control circuits in the plant.
- Power quality solutions can range from thousands of dollars to millions of dollars.

Effect of Equipment Sensitivity Information on Cost of PQ Solution



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Recommendations for Hardening Magnet Wire Plant – Distributed Power Conditioning

- A number of controls in the magnet wire plant are fed from AC power.
  - One recommendation is to provide small “batteryless” power conditioners for equipment supplied by AC control transformers.
  - The power conditioners can be installed on the secondary side of the control power transformers.

Example Batteryless Power Conditioners

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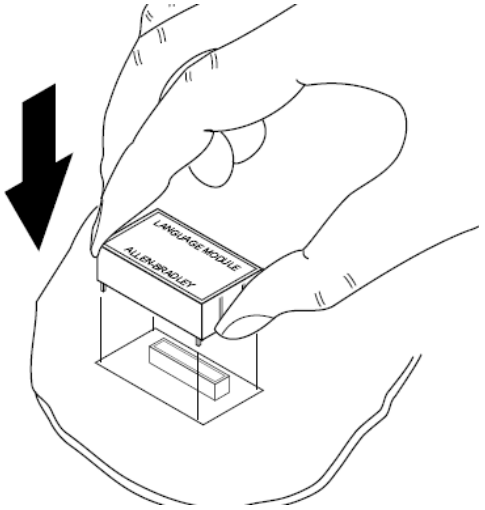
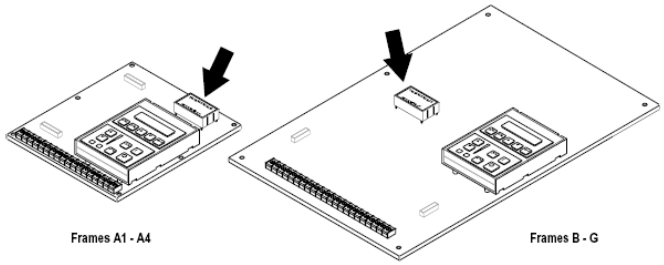
Recommendations for Hardening Magnet Wire Plant – Firmware Upgrade

- The magnet wire plant uses several AC drives of a single make.
- AC drives are susceptible to voltage sags in which the DC bus level drops to 81% of nominal or less.
  - Test results at EPRI in the past indicate lowering the DC bus trip level will greatly increase the ride-through.
- Each drive must be retrofitted with a new language module firmware revision to allow a lower DC bus voltage trip setting to 50%.
- This is a typical low-cost solution as firmware upgrades are relatively inexpensive.





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Cost-Benefit Analysis of Recommended Power Quality Improvement Solutions

- Below is a summary of the recommendations and estimated typical costs based on the first two recommendations in the previous slides (distributed power conditioning and firmware upgrades).
- For the purposes of cost calculation for the third recommendation (using a centralized power conditioning system), a mid-range price of $300 per kVA will be used.
  - The centralized method equates to roughly $600,000 per 2-MVA transformer or $1.8 million for 3 transformers.

Cost for Distributed Power Conditioning and Firmware Update Recommendations

Area	Recommendation	Number Required	Cost
Rod Mill	Small batteryless power conditioners	2	$2,780
Horizontal Lines	Drive firmware upgrade kit	352	$70,400
Vertical Lines	Drive firmware upgrade kit	72	$14,400
Enamel System	Small batteryless power conditioners	1	$1,690
Lubricant System	Small batteryless power conditioners	1	$1,690
Mechanical Room Systems	Small batteryless power conditioners	1	$1,690
	Drive firmware upgrade kit	2	$400
		Total Cost	**$93,050**

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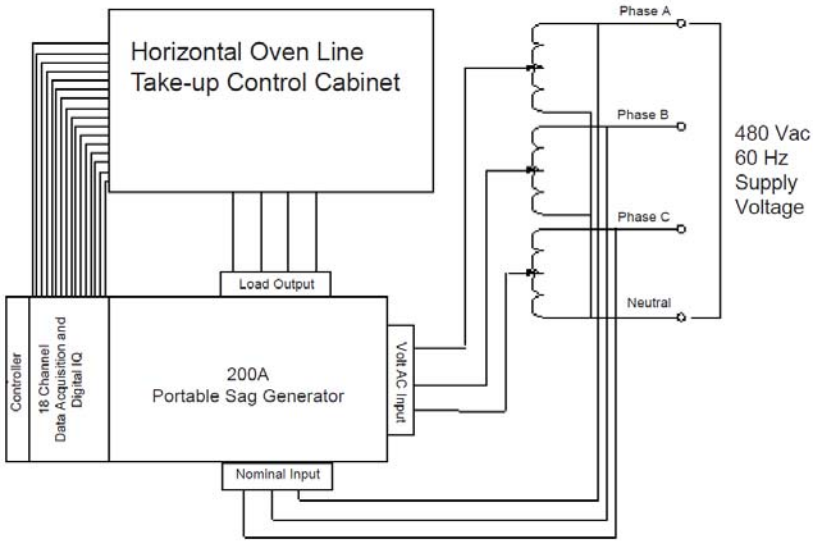
Test Validation of Recommendations (1)

- PQ testing was performed on one selected line to evaluate the actual line susceptibility as well as to validate the low-cost recommendation of upgrading firmware and setting drive bus trip level to 50%.
  - Line testing was conducted to prove firmware upgrades improved the ride-through performance.
- The testing strategy was to characterize the AC drives with the firmware upgrade installed and then test again without the existing firmware revision.
- The voltage sag generator was placed in series with the 480-Vac source and the take-up control.



EPRI Voltage Sag Generator
Electrical Hook-Up

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Test Validation of Recommendations (2)

- The oven was tested at various voltage levels and durations to characterize the ability of the equipment to ride through voltage sags.
- Below lists the test points agreed upon by the team and all voltage sags were performed phase to phase.

Horizontal Line Take-Up Drive Cabinet

Voltage Sag Test Points

Test Number	Sag Duration (60-Hz cycles)	Sag Duration (seconds)	SEMI F47 Ride-Through Curve Sag Depth (% Vnominal)
1	3	0.05	50
2	6	0.1	50
3	12	0.2	50
4	30	0.5	50
5	60	1	50

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Test Validation of Recommendations (3)

- During the sag testing of the horizontal line with the firmware upgrades, it was discovered that a two-phase sag of any duration to 60 cycles with a magnitude down to 35% nominal would not trip AC drives off-line.
  - Testing below 35% of nominal was discontinued as the inrush current was in excess of 90 amps and might destroy the rectifiers in the drive.
- Similarly, the test was repeated on a line with no firmware updates installed.
  - The unprotected drive yielded its first trip at 12 cycles, 70% nominal by shutting down the drive, thus breaking the magnet wire.
- Repeated testing revealed that the unprotected AC drives tripped more often.

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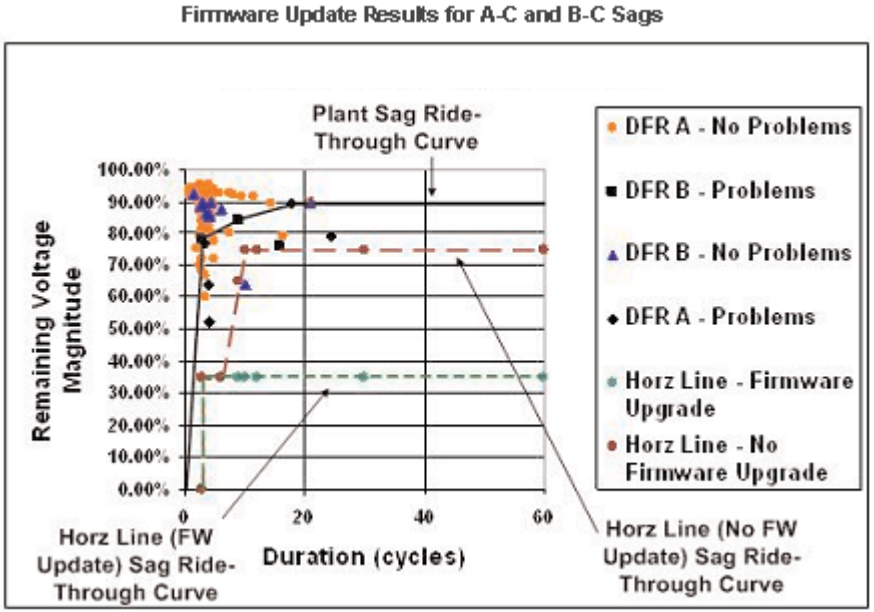
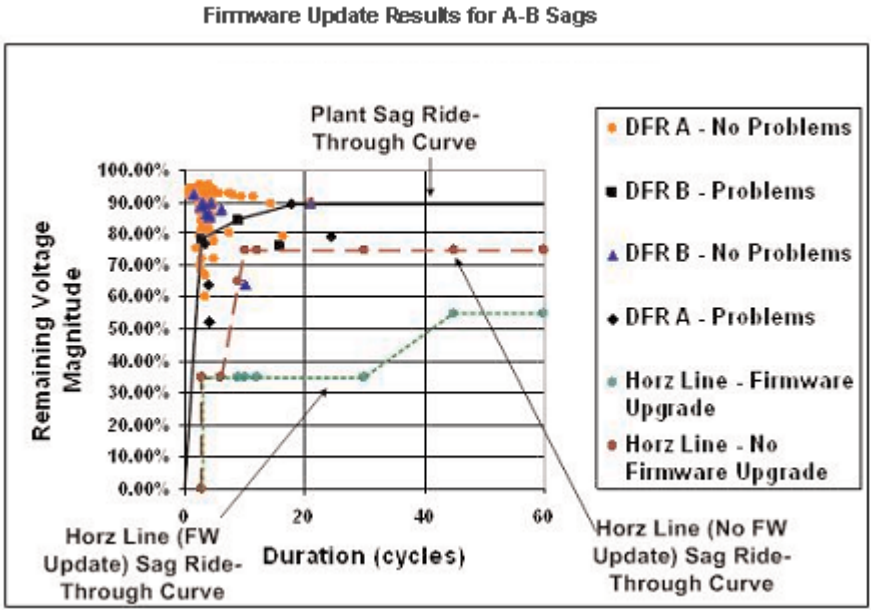
Test Validation of Recommendation (4)

- Based on the testing, sag ride-through curves were compiled.
- ***These curves show that a simple update to the drive firmware and resetting of the DC bus trip levels to 50% will significantly harden the line's susceptibility to voltage sags.***





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Industrial Case Study: Monitor Manufacturer

The “Engineering” of Embedded Solution

- Initial dialogue established between plant personnel and utility PQ group.
- Remote gathering of information, plant/equipment one-line diagrams, process upset logs, PQ monitoring data.
- One week investigation at the plant
  - Get buy-in from the process managers
  - Understand the process
  - Talk with the process floor people
  - Evaluate sensitivity
  - Investigate hidden weak links
  - Evaluate solution options
  - Cost benefit analysis
  - Recommendation to process managers

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Production Lines

- Line A manufactures 19" CRTs for monitors with provisions for 21"
- Line B manufactures flat panel 19” CRTs for monitors with provisions for 17”.
- Pegasus Line manufactures 17” CRTs for PC monitors.
- 32” line manufactures TV CRTs .
- 27” Line manufactures TV CRTs
- 20” Line manufactures TV CRTs.

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Financial Impact of Three Events

Date	Impact	# of Units Rejected (A)	Downtime in Minutes	# of Units missed due to downtime (based on 28 second Mercury Index time) (B)	Total # of Units missed (A) + (B)	Total Cost (based on $180 per unit)
11/19/98	Power fluctuation caused CS light houses to trip	30	20	43	73	**$13,140**
11/23/98	Power Glitch AG, SCR, PII, Lost all screening	73	48	103	176	**$31,680**
01/26/99	Power glitch in screening process	44	10	22	66	**$11,880**
Total		**147**	**78**	**168**	**315**	**$56,700**

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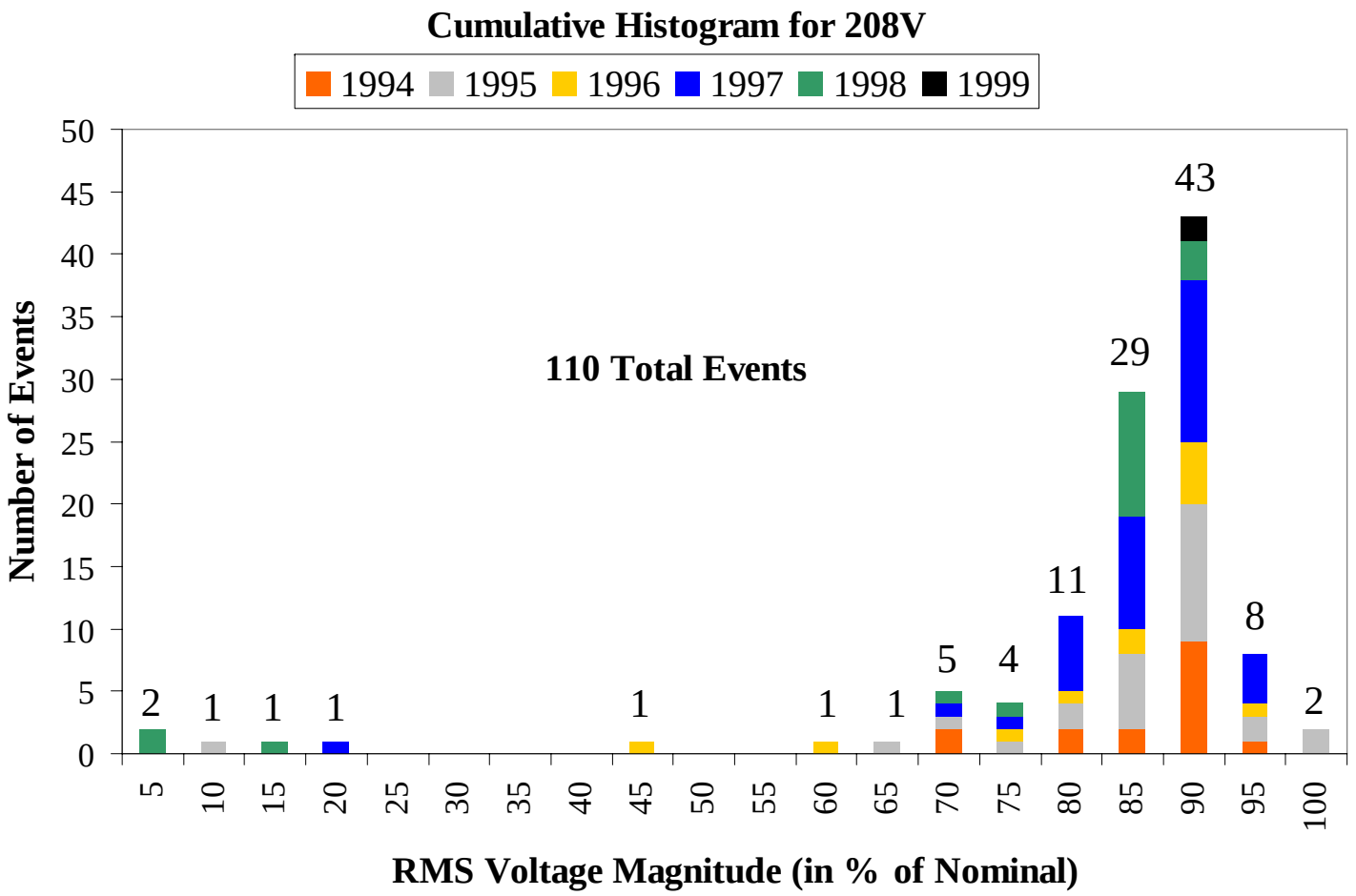
Voltage Sag Characteristics Inside the Plant



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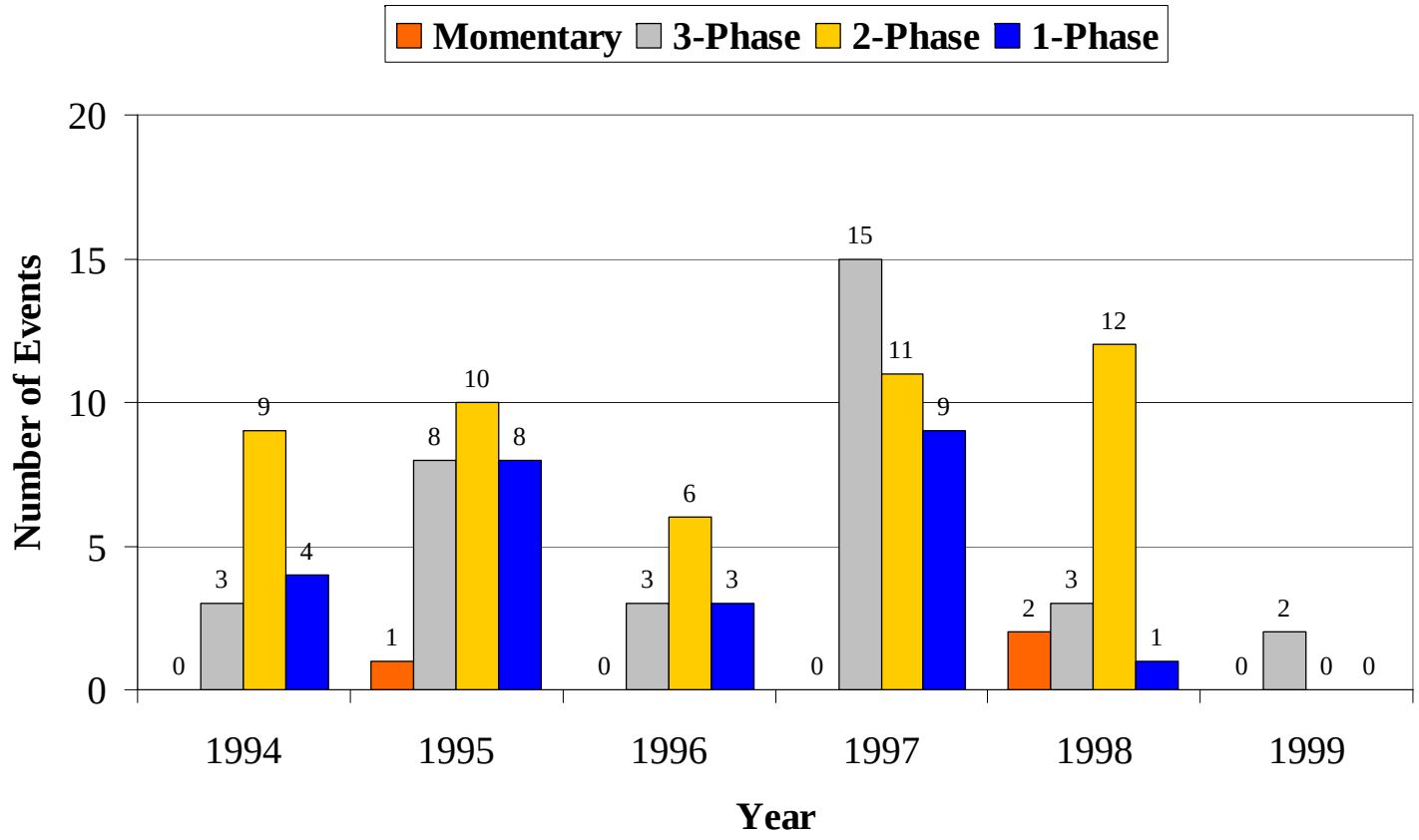
Type of Events



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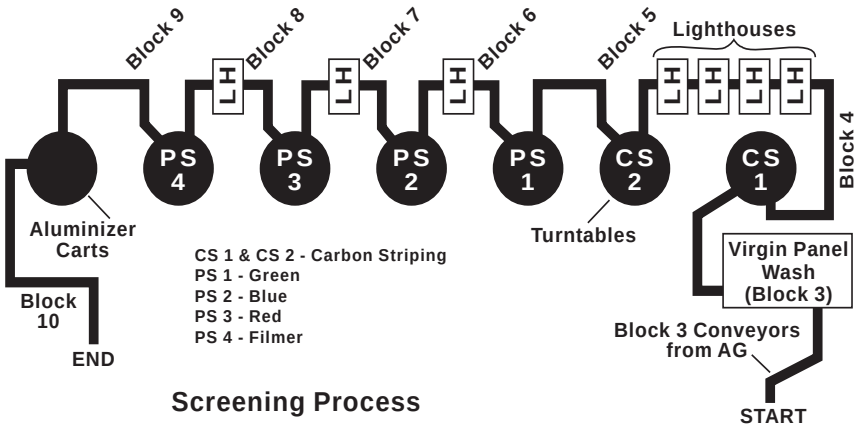
Critical Process: Screening



Screening Process Flow Diagram

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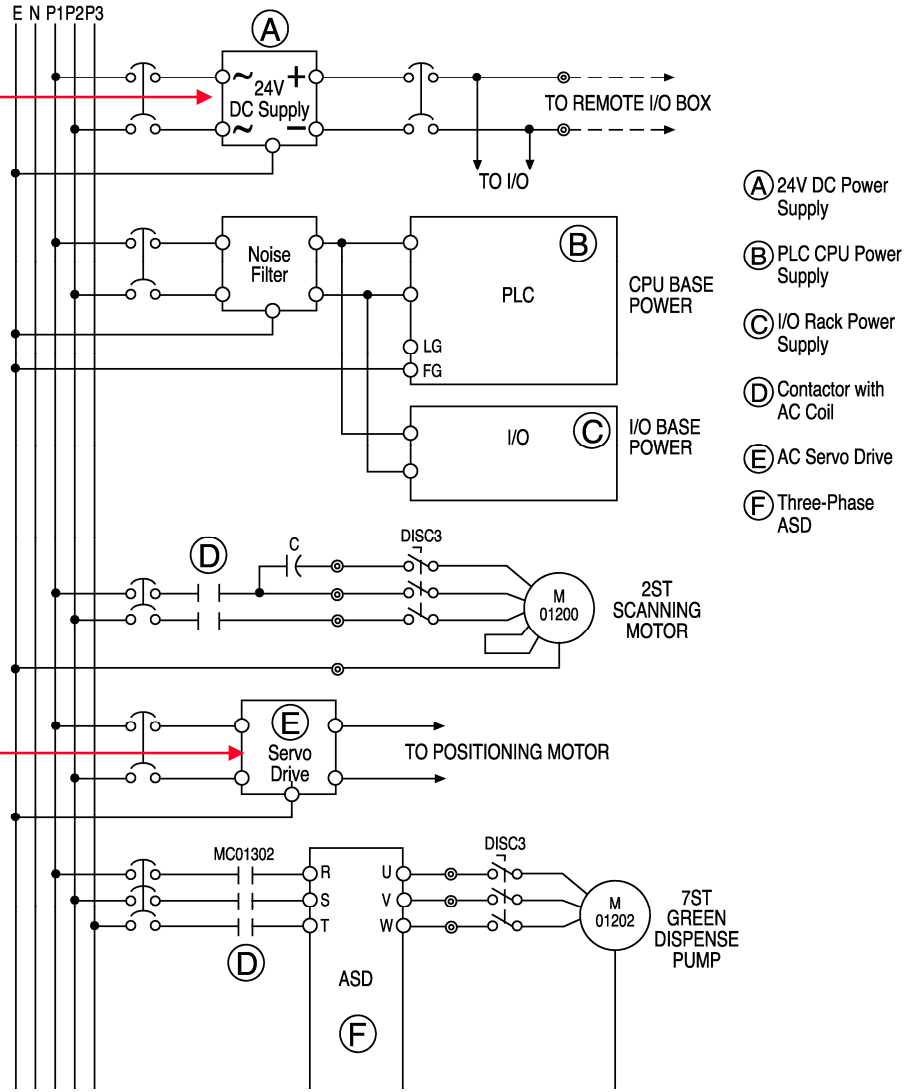
Sensitive Equipment



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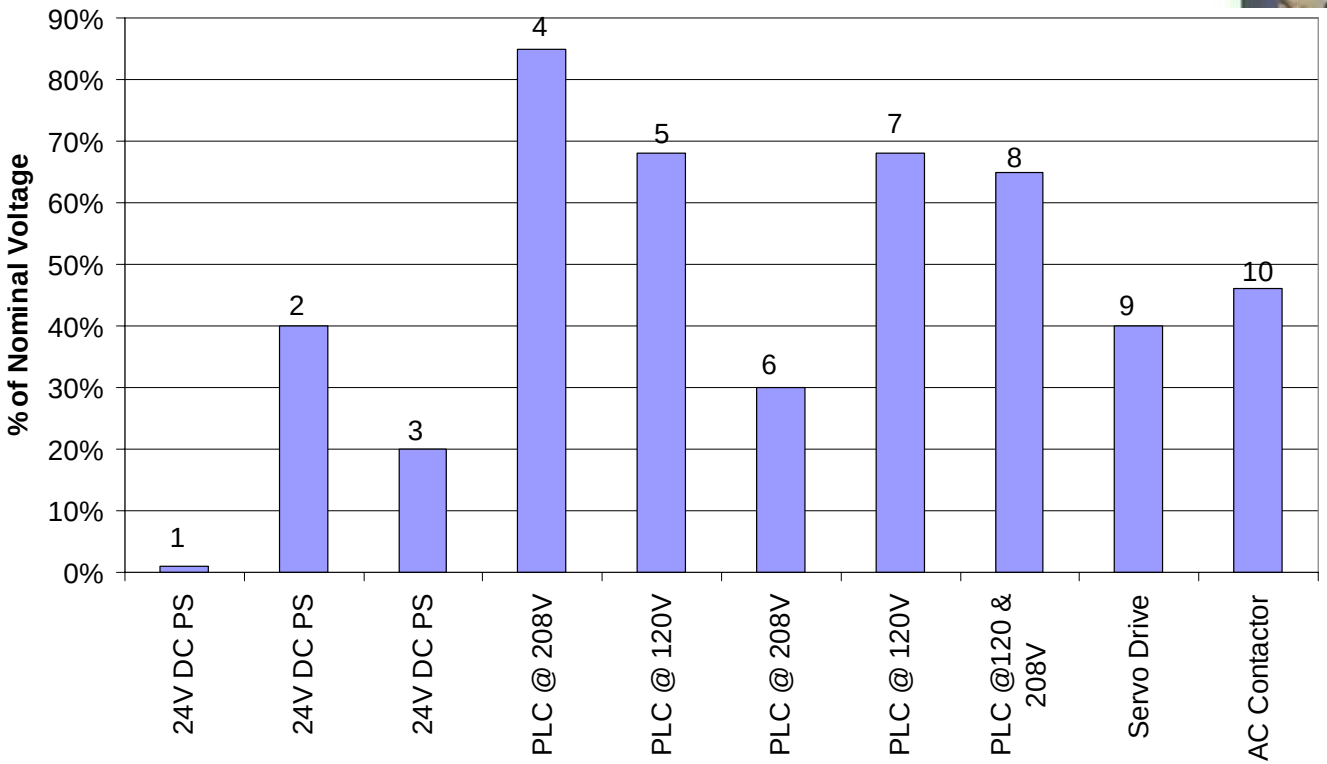
How Sensitive?

(Higher Bar Means More Sensitive)



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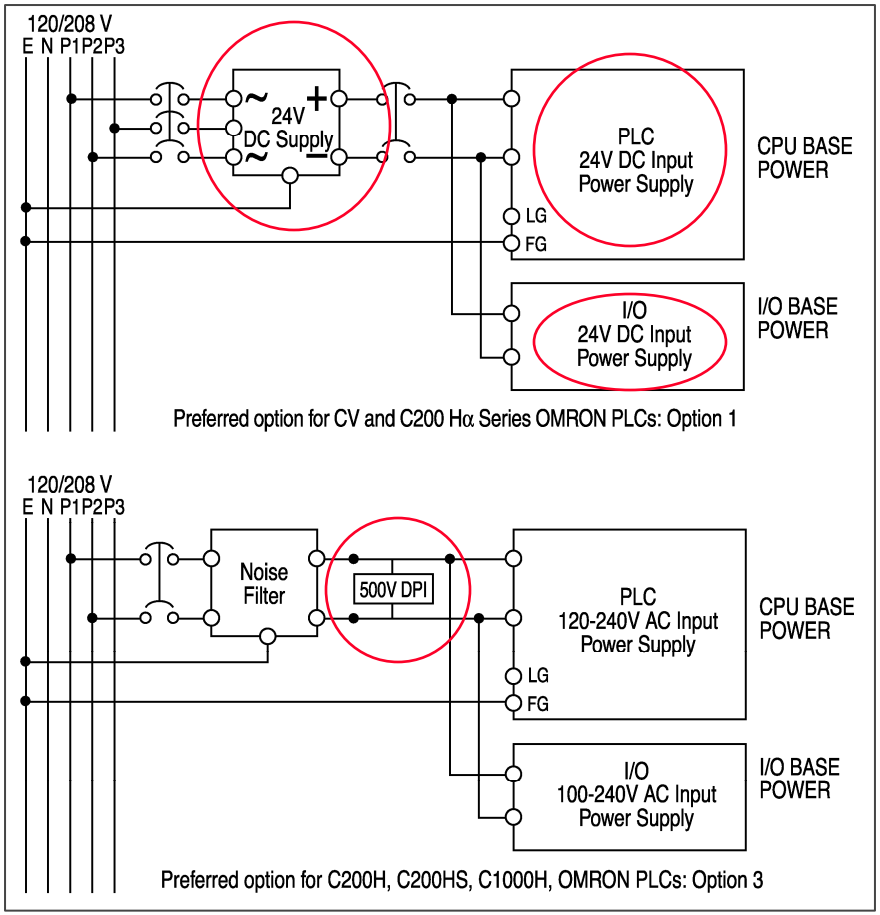
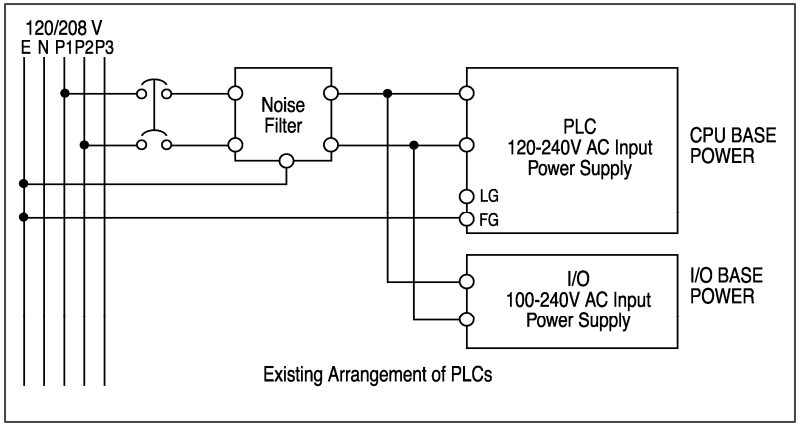
Embedded Solution





Change PLC Input from AC to DC input.

Use a 3-Phase AC input to 24VDC output Power supply.

If PLC AC power supply is integrated to the Module use a small power conditioning (e.g., Dip Proofing Inverter or CVT).

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AC Versus DC Input for PLCs

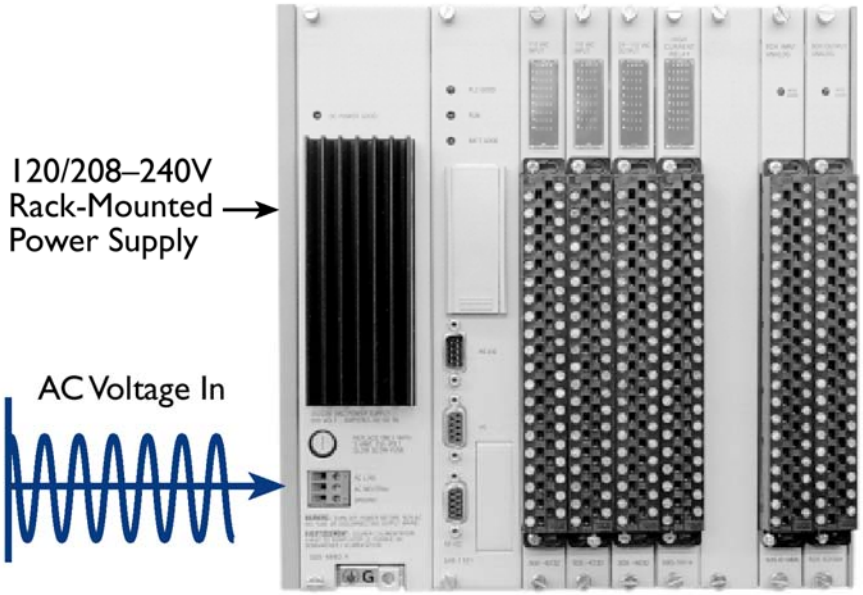

Figure 1. A rack-mounted PLC power supply that requires AC voltage (120/208-240 volts)

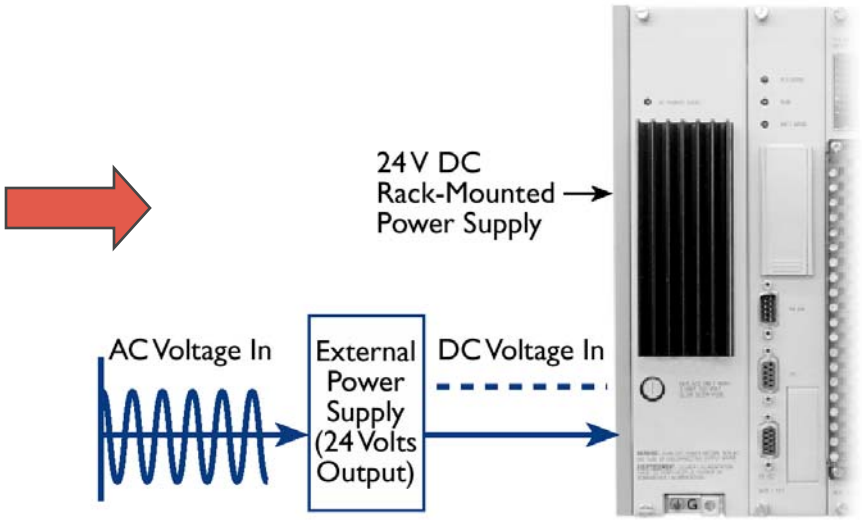

Figure 2. External power supply that provides 24 volts DC to the rack-mounted PLC power supply.

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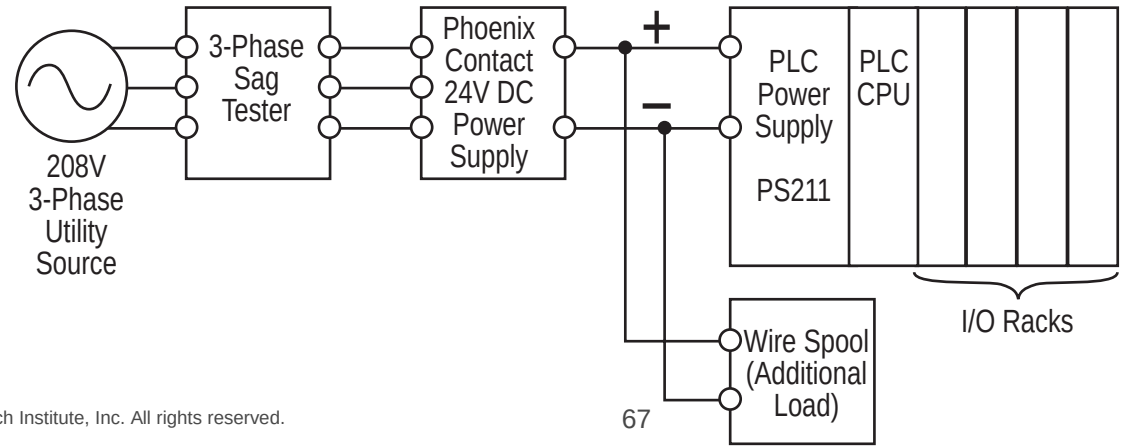
How Effective is a 3-Phase AC Input to 24V DC output Phoenix Contact PS

PLC Power Supply unit	24V DC Source	Loading on 24V DC Source	Voltage Sensitivity Threshold (in %) for 30 Cycle Ride-Through		
			Three Phase Sags	Two-Phase Sags	Single-Phase Sag
CV500-PS211	Phoenix Contact	20%[1]	0%	0%	0%
CV500-PS211	Phoenix Contact	35%	45%	0%	0%
CV500-PS211	Phoenix Contact	60%	50%	0%	0%



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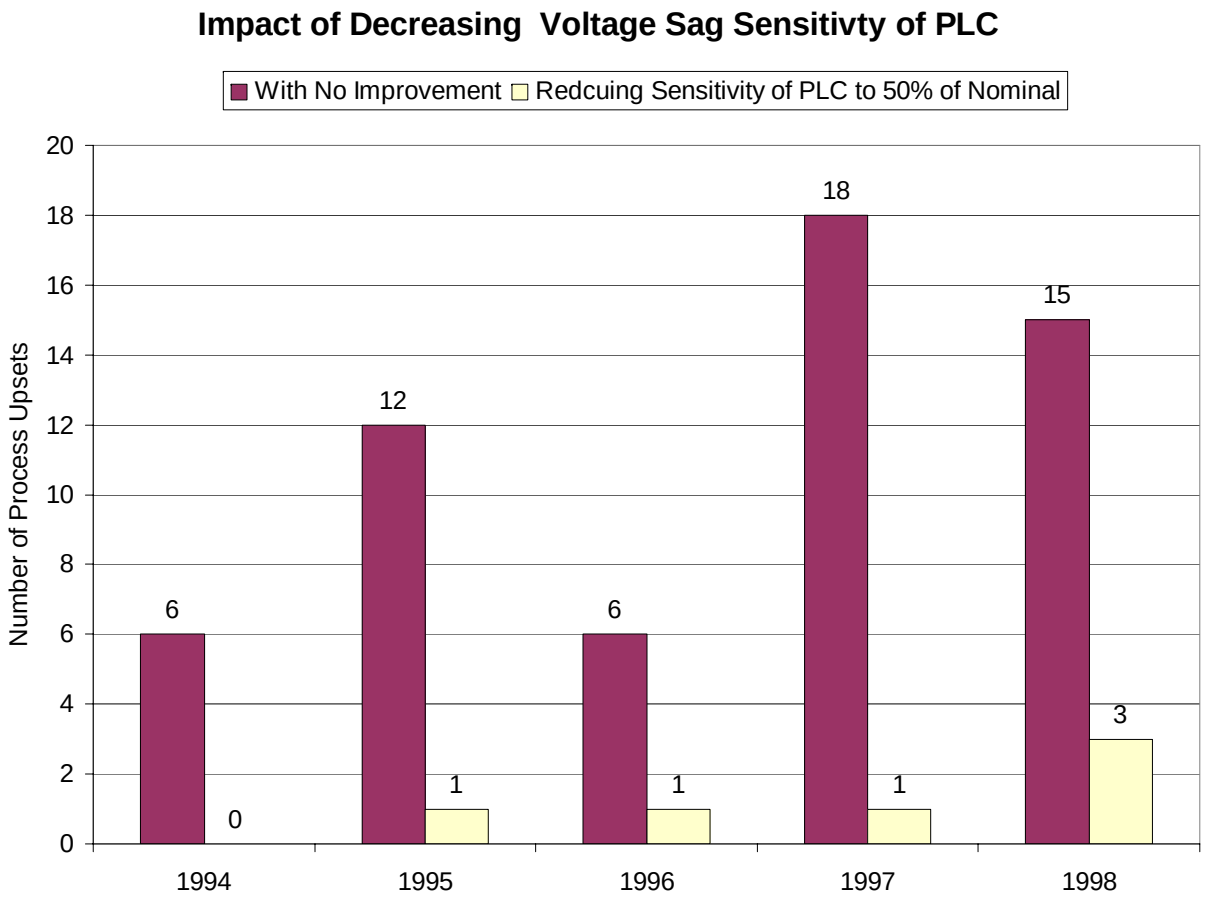
How Effective is this Solution?



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Targeted Recommendation Based on PLC Type

	PLC Types	Existing 100-240V AC PLC, I/O Rack Power Supply	Replacement 24V DC Power Supply
	CQM1 (Small Range)	• CQM1 PA-203 • CQM1 PA-206	Not required; Existing power supply can withstand sags down to 30% of nominal voltage
	C200Hα (Mid Range)	• PS223 • PS22E	• PA204
	CV Series: 500, 1000, 2000, M1 (Large Range)	• CV500-PS221 • CVM1-PA208 • 3G2A5-PS22-E	• CV500-PS211 • 3G2A5-PS212-E
	C200H, C200HS, C1000H (older model PLCs)	Power Supply Integral to CPU Unit	Not available for PLCs with integral power supply; Requires 500VA DPI unit for PLC and I/O Rack power supply

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Lessons Learned

- In designing new process lines use DC input controllers wherever possible.
- Use a robust DC source for all your DC inputs (such as, 3-Phase AC to 24V DC power supply)
- Know the sag immunity of your DC power supplies in your plant.
- See PEAC PQ Brief No. 49: Ride-Through Characteristics of PLC AC and DC Power Supplies

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